SHEAR STRENGTHENING OF SKEW RC BEAMS USING CARBON FIBER REINFORCED POLYMER STRIPS

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JULY 2009

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By

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7467

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Civil Engineering)

July 2009

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CIVIL ENGINEERING)

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July 2009

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NOOR SAFWAN BIN MUHAMAD

ABSTRACT

This study demonstrates the shear strengthening of skew Reinforced Concrete (RC) beams using Carbon Fiber Reinforced Polymer (CFRP) strips. Skew RC beams are widely practiced in the construction of bridges and flyovers. Nowadays there are many researches done to study the effect of CFRP on straight beams but not on skew beams, so this research provide a good overview on the effect of CFRP on skew beams as skew beams did not only suffer vibration like straight beams but also torsion effect due to its shape. As there are many cases of failed bridges and flyovers reported worldwide including in Malaysia, researchers now aggressively find strategies to repair and retrofit those structures instead of choosing to demolish and reconstruct it is as the costs become the main constraint. CFRP is chosen as one of the alternative material to restore the deteriorating and deficient structures because it comes with many advantages such as corrosion resistance, a high strength-to-weight ratio and ease of handlings thus can reduce the maintenance costs. In this study, six simply supported 150mm x 230mm x 2000mm RC beams were tested to evaluate the effect of CFRP in strengthening skew beams. Two of the beams were treated as control beams while the other four were wrapped up with CFRP strips. To study the effect of CFRP configuration on the strengthening of skew beams, two different configurations were applied while to study the effect of skew angle on the shear strength of the beam, 3 of the beams were tested with 15° skew while the other 3 were tested with 20° skew. From the static load test, the strengthening of skew beams using CFRP varied from 21.08% up to 43.47% and from this variation, the effect of CFRP configuration and skew angle on the strength of the beams were determined. Recommendation for future works were provided at the end of this report to obtain more details on the relation between skew angle and CFRP configuration on shear strengthening of skew beams so that analytical and numerical approach can be established.

ACKNOWLEDGEMENT

This whole project and report would not have been possible without a passionate and active participation and support from various peoples. I thank all of them from the bottom of my heart in making this final year project fun and fruitions program.

First and foremost, praise to God almighty. With His blessing, helpfulness and loveliness, He gave me the strength and health to complete this Final Year Project. My thanks go to my parents for their support and prayers for my success.

My greatest gratitude goes to my supervisor, Associate Professor Dr Nasir Shafiq for his excellent guide, incisive advice, wisdom and encouragement towards the accomplishment of this project.

Also special thanks to laboratory technologists, Mr Johan and Mr Hafiz for their helps towards the project's completion.

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ABBREVIATIONS

AFRP	Aramid Fiber Reinforced Polymer
CFRP	Carbon Fiber Reinforced Polymer
FRP	Fiber Reinforced Polymer
FYP	Final Year Project
GFRP	Glass Fiber Reinforced Polymer
OPC	Ordinary Portland Cement
PG	Post Graduate
RC	Reinforced Concrete
UTP	Universiti Teknologi PETRONAS

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Many structures throughout their lifetimes require strengthening for several reason such as corrosion of materials, structural and fire damage, change of use and increased loading, inadequate design, poor quality construction and recently to protect against seismic loading. For example, existing bridges majorly were designed for traffic loads lighter than the ones common today. By evaluating the strength, once it indicates that the flexural or shear capacity is insufficient, the structural engineers are the one who is accountable in find out ways to tackle this problem. There are several ways can be considered by the engineers where the safest way is by demolishing and reconstructing the bridges according to the new traffic load. However, as engineers must not only thinking of the way to resolve the issue but at the same time thinking about the economic impacts, repairing and retrofitting the existing bridges are the best way to solve this structural problem.

Decades before, steel plates are widely used to strengthen the bridges and other civil structures; however the corrosion and increased in steel prices has make the maintenance costs become huge thus considered as no more reliable. The researchers are finding ways to come out with a new shear strengthening techniques such as by using composite materials which is currently seen as capable alternatives. The application of carbon fiber reinforced polymer (CFRP) in construction industry is growing as a solution for strengthening or retrofitting the structures, other than that CFRP also is believed to be an alternative for prestressing materials. Researchers have proved that the use of CFRP is cost-effective in a number of field applications in strengthening concrete, masonry, steel and timber structures.

1.2 Problem Statement

This project focusing mainly on the application of CFRP strips in strengthening the skew beams in shear. Although there are several researches have been conducted on the strengthening of Reinforced Concrete (RC) elements using CFRP strips, most of them only deal with straight, rectangular concrete beam. For a skew beam which is widely practiced in the construction of bridges and flyovers, it might not only suffer vibration like straight beam but due to its shape, skew beam might suffer the torsional effect so a study focusing on skew beam must be conducted separately. This project demonstrates the behaviour of CFRP strengthened skewed RC beams to justify the effect of CFRP strips in shear strengthening of bridges structures. Although there are several drawbacks reported in using CFRP, for example it have no ductility which could lead to undesirable brittle failure of the strengthened elements and the price which is more expensive compared to steel plates, the advantages of using CFRP is believed to be a more dominant criteria to be chosen as strengthening material.

1.3 Objectives and Scope of Study

1. To determine the best configuration of CFRP wrapping on skew beam for maximum enhancement of beam shear capacity. The importance of this objective is to determine whether the effectiveness of CFRP techniques is affected with different inclination of CFRP attached. This can be justified by comparing the ultimate strength of the skew beams strengthens with different slanting of CFRP.

2. To determine the effect of beam's skew angle on the strengthening of beams using CFRP. The importance of this objective is to ensure that CFRP is applicable for any skew of beams as in the real life, the skew of beams varied along the bridges. For this project, this condition can be demonstrated by varying the degree of beam inclination to investigate whether different skew of beams might result in different value of the ultimate strength.

The scope of study for this project only covers the effect of CFRP on shear strengthening of skew RC beams. Six test beams with the same 2Y12 tensile reinforcement, 2Y12 compressive reinforcement and R6-300 links were casted and tested using 500kN dynamic machine. In achieving the objectives, the testing was done with two configuration of CFRP and two skew angles of the beams.

To ensure that this project can be completed within the time frame, the beams were tested using static load test because for dynamic load test, it might take months to be completed. As bridges experience both static and dynamic loading, applying static load test for this case can be considered as relevant. The ultimate loads that can be sustained by the beams before it failed were considered as the shear strength capacity of the beams. These shear strength capacity were compared to analyze the strength improvements contributed by CFRP. Throughout the completion of this project, some improvements were made where applicable to avoid failure due to poor construction practice.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Concrete Structures

2.1.1 Shear Behaviour

To be able to strengthen concrete structures for shear, the understanding of the shear behavior and the different ways a concrete structure can reach failure are very important. Figure 2.1 below shows a simply supported rectangular concrete beam depicting possible failures.

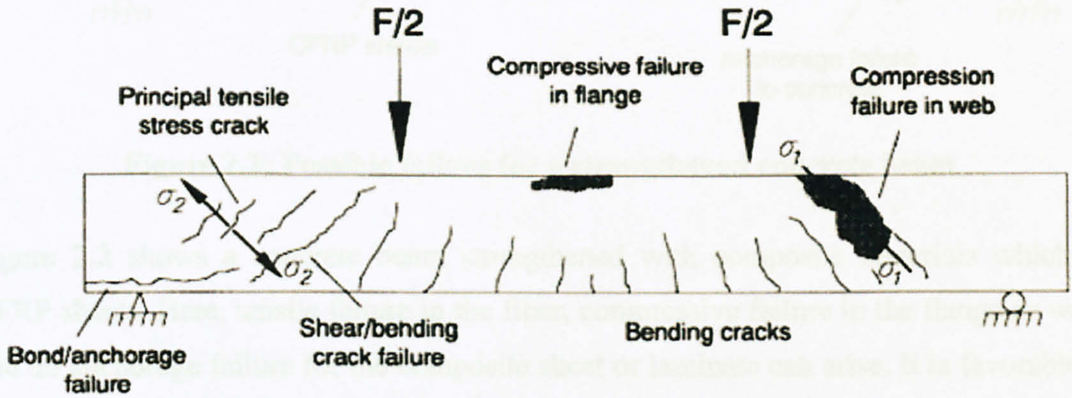


Figure 2.1: Possible failure for a simply supported rectangular concrete beam

In normal situations a concrete structure is designed to reveal large deformations before failure, which means that the failure is often a bending failure. According to Bjorn (2002), a traditional shear failure often starts with combined bending and shear that develops into a shear crack. The failure is shear failure in the highest tensile region where σ_2-stress occurs. The highest shear stress is the build-up in the centre of the cross-section of the beam, if the beam is rectangular and has a uniform reinforcement.

2.1.2 Shear Strengthening

In normal cases, vertical steel stirrups take care of the built-up stresses. However, if for some reason the structure needs to be strengthened for shear; for example by using CFRP sheets, Bjorn has found other possible failure modes that can arise such as shown in Figure 2.2.

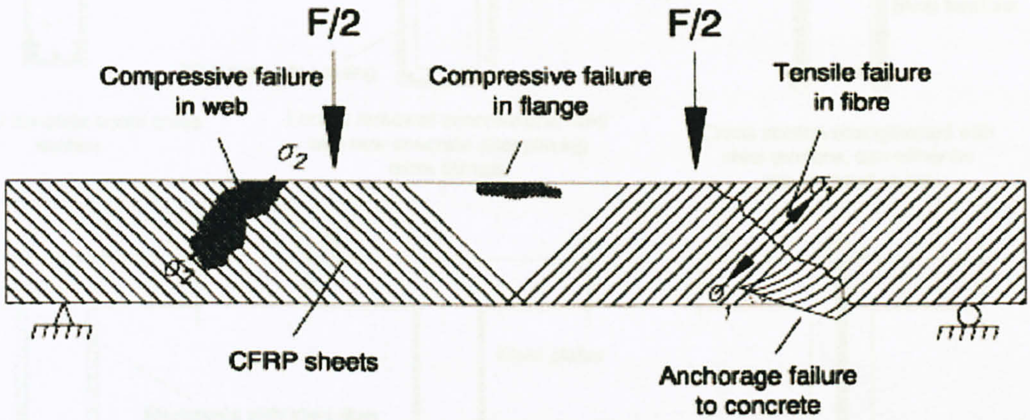


Figure 2.2: Possible failure for a strengthened concrete beam

Figure 2.2 shows a concrete beam strengthened with composite materials which is CFRP sheets. Here, tensile failure in the fiber, compressive failure in the flange or web, and an anchorage failure for the composite sheet or laminate can arise. It is favorable if a bending failure arises before any of the shear failures since this type of failure often arises without any forewarning. The anchorage failure can easily be taken care of either by wrapping the sheet around the beam or in cases with T-sections, anchoring the sheet in the compressive zone.

Figure 2.3 in Page 6 shows a T-section of a beam or a slab. The section needs strengthening for shear. Six different traditional methods to solve this problem are presented. Method (a) is probably the most commonly used. Here, existing concrete on the top of the slab is removed, new stirrups are mounted around the existing cross section and new concrete is cast or sprayed onto the structure. If adhesion between the new and old concrete can be assured, method (a) is good from a technical standpoint. A new wider section with the steel reinforcement anchored in the compressive zone will give a higher shear capacity for the structure. However, the method is both time consuming and in many cases not cost effective.

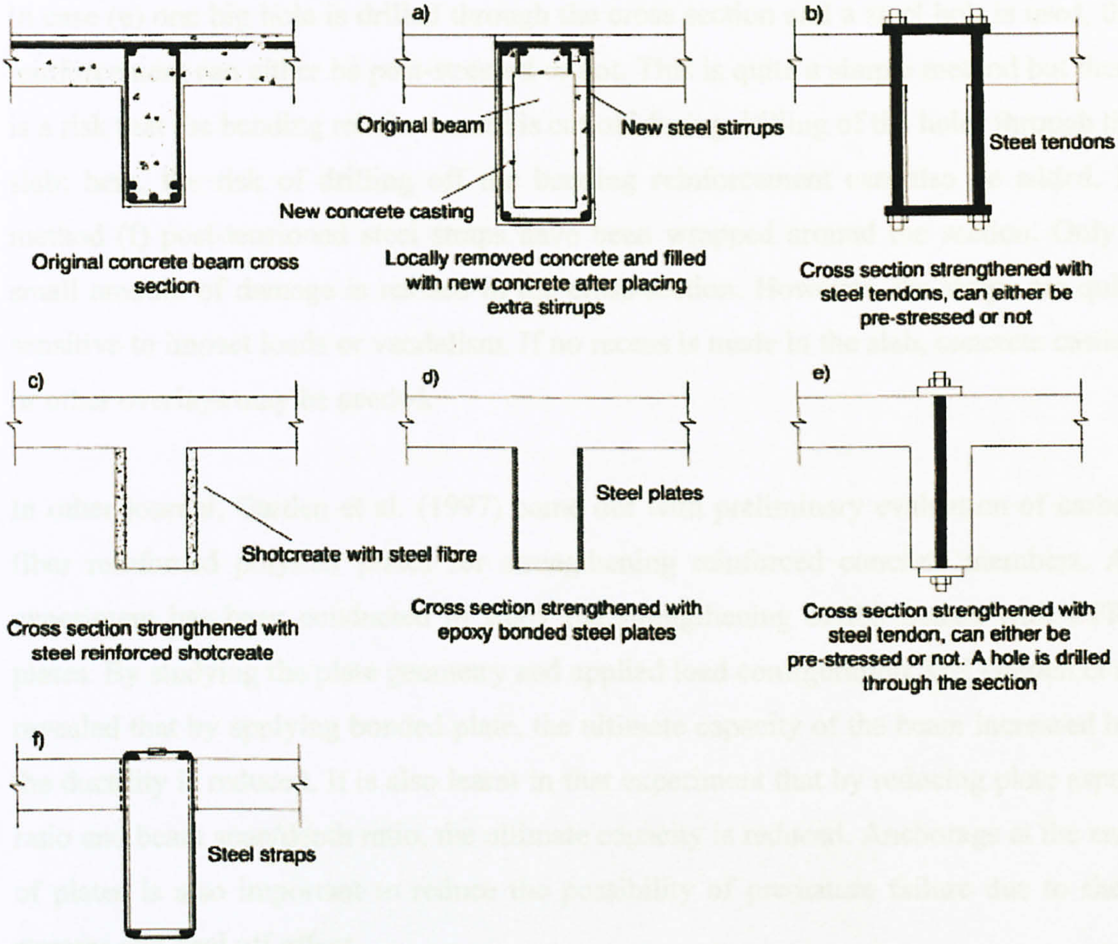


Figure 2.3: Traditional shear strengthening methods

Method (b) has also been used frequently for shear strengthening in the past. This method is a little bit easier to carry out than method (a), but there is a risk that the bending reinforcement is cut off during drilling of the holes through the slab. Concrete casting above the bolts on the slab can also be necessary. Case (c) can be used in cases where a limited shear strengthening effect is asked for. A drawback with this method is that the strengthening material is not anchored in the compressive zone. This is also the case for method (d) where steel plates are bonded to the side of the structure. Bonded steel plates are the forerunners for bonded CFRP plates or sheets, however as the steel plate is very prone to corrosion, this method is considered ineffective in term of the costs in the long run due to maintenance.

In case (e) one big hole is drilled through the cross section and a steel bolt is used, the reinforcement can either be post-stressed or not. This is quite a simple method but there is a risk that the bending reinforcement is cut off during drilling of the holes through the slab; here, the risk of drilling off the bending reinforcement can also be added. In method (f) post-tensioned steel straps have been wrapped around the section. Only a small amount of damage is needed in the cross-section. However, the straps are quite sensitive to impact loads or vandalism. If no recess is made in the slab, concrete casting or other overlays may be needed.

In other journal, Garden et al. (1997) come out with preliminary evaluation of carbon fiber reinforced polymer plates for strengthening reinforced concrete members. An experiment has been conducted to study the strengthening of RC beams with CFRP plates. By studying the plate geometry and applied load configuration, HN Garden et al. revealed that by applying bonded plate, the ultimate capacity of the beam increased but the ductility is reduced. It is also learnt in that experiment that by reducing plate aspect ratio and beam span/depth ratio, the ultimate capacity is reduced. Anchorage at the ends of plates is also important to reduce the possibility of premature failure due to shear stresses and peel off effect.

Jin et al. (2005) has conducted experiment by testing two control beams and sixteen beams strengthened with CFRP laminates to investigate whether the preload level influence the flexural behavior of strengthened beams. From the experiment, it concluded that the preload level has more influence on the stiffness and beam deflection, both at post-cracking and post-yielding stage, than on the ultimate flexural strength. However, the peeling of CFRP laminates become the main failure mode to the strengthened beam provided that the shear capacity of the beam are sufficient.

2.2 Skew Beam

2.2.1 Introduction to Skew Beams

Skew beams are widely practiced in the construction of bridges throughout the world. For example, from the official website of Bandra Worli Sea Link Project, a project under DAR Consultants which is a well known structural consulting firm from United Kingdom, http://www.bandraworlisealink.com/abroad-pro.html, it is stated about Corinth Canal Bridge, Greece where the project conditions required that the highway design be strictly adhered to a 600m radius curve at a skew of 51 degree to the axis of the canal. The bridge is a concrete cable stayed structure of 160m main span and 50m side spans supported from two towers one on each side of the canal. The deck is carried by a parallel plane of cables along the median. The towers are inclined towards the outside of the curve to make the stay cables tangential at the point of connection to the deck and are stabilized by the transverse stays which are anchored to the outrigger beam at each tower support. Figure 2.4 shows the architectural illustration on the Corinth Canal Bridge. This bridge is a very good example on the application of skew beams in a large scale construction.

Figure 2.4: Corinth Canal Bridge, Greece

2.2.2 Defect of Skew Beams

Rapid development has resulted in a swift increased of traffic that use the bridge to commute everyday, this charging of bridge function from a lower service load to a higher service load has resulted in major structural failure throughout the world. This phenomenon becomes worst due to the rotation of skew bridges in the plane due to torsion effect. Researchers have come out with several ideas to solve the problem of torsion. Ding et al. (2005) for example has proposed the application of slant-leg frame skew bridge without abutment. The study on the slant-leg rigid frame bridges without abutment has shown that this method can restrain the rotation of skew bridges in the plane to the utmost extent because of its structural characteristics and can fundamentally solve the tough defect of skew bridges.

2.3 Carbon Fiber Reinforced Polymer (CFRP)

2.3.1 History

Carbon Fiber Reinforced Polymer (CFRP) comprises fibers of high tensile strength within a polymer matrix. The carbon fibers, in a matrix such as vinylester or epoxy are preformed to form plates and stripes under factory condition, generally by pultrusion process. Darby (1998) in his publication has stated the advantages of using CFRP plates for strengthening such as the strength of plate which is likely to be at least three times the ultimate strength of steel for the same cross-sectional area, other than that, the density of CFRP plate which is 20% of the density of steel make the CFRP weight less than 10% of the weight of steel of the same ultimate strength.

In terms of transport, the weight of plates is so low that a 30m long composite plate may be carried out by a single man and it can be bent into a coil as small as 1.5m diameter which can be transported in a car or small van. The flexibility of plates also enables strengthening to be completed within confined spaces. Compared to the steel plate, CFRP plate did not suffer deterioration or corrosion thus in the long run, it is financially efficient because it did not require maintenance for example painting which may incur traffic disruption and access costs as well as the work costs.

Many of the practical advantages described above make the use of CFRP in the construction industry growing as a solution for strengthening, repairing and retrofitting both concrete and steel structures. Before the emergence of CFRP, methods applied as a solution included bonding and welding of additional steel plate and placing of additional concrete, however due to the increase in the price of raw materials and the disadvantages come with it such as corrosion of steel, these processes can be expensive, labour intensive and time consuming.

Retrofitting has become the increasingly dominant use of the material in civil engineering, and applications include increasing the load capacity of old structures such as bridges that were designed to tolerate far lower service loads than they are experiencing today, seismic retrofitting and repair of damaged structures. Retrofitting is popular because the cost of replacing the deficient structure can greatly exceed its strengthening using CFRP. Due to the incredible stiffness of CFRP, it can be used underneath bridge spans to help prevent excessive deflections, or wrapped around beams to limit shear stresses.

Discussing on CFRP bars, it can be used as a replacement of steel to reinforce concrete structures. More commonly they are used as prestressing materials due to their high stiffness and strength. The advantages of CFRP over steel as a prestressing material, namely its light weight and corrosion resistance, enable the material to be used for niche applications such as in offshore environments. CFRP is a more costly material than its counterparts in the construction industry, glass fiber reinforced polymer (GFRP) and aramid fiber reinforced polymer (AFRP), though CFRP is generally regarded as having superior properties.

Strengthening or rehabilitation of RC, prestressed concrete and steel members using externally bonded CFRP were discussed by Hollaway and Leeming (1999) in their publication. Since the external plating and its application as a strengthening technique has only be made possible by the development of suitable adhesives, consideration is initially given to the types of adhesive which may be used for external plating bonding and their requirements for this application, the same goes to the surface preparation techniques. The bonding of concrete with epoxy resin was demonstrated in the late 1940's and the early development of structural adhesives was recorded since 1960's.

2.3.2 Research and Development

More researches using CFRP continues to be done for both retrofitting and as an alternative to steel as a reinforcing or prestressing material. Cost remains an issue and long term durability questions still remain. Some are concerned about the brittle nature of CFRP, in contrast to the ductility of steel. Though design codes have been drawn up by institutions such as the American Concrete Institute, there remains some hesitation among the engineering community about implementing these alternative materials. In part this is due to a lack of standardization and the proprietary nature of the fiber and resin combinations on the market, though this can be an advantage where the material properties can be tailored to the desired application requirements.

Recently the application of CFRP has been growing steadily to strengthen the structure in both flexural and shear. Several researches have been done in the application of CFRP to strengthen the straight, simply supported beams in both shear and tensile. Alex et al. (2001) have done the experimental investigation to study the effect of composite carbon fabric shear reinforcement on the ultimate strength and behaviour of a reinforced concrete beam in the absence of the stirrups in the shear span. In the conclusion segment, it is stated that the CFRP shear contribution to the shear capacity of strengthened reinforced concrete beam depends on many parameters including the surface strengthened by composite fabrics, the composite fabric shear reinforcement ratio, the span to effective depth of beam ratio and the strength of composite fabrics.

The experimental results obtained shows that as the composite fabric area increased the contribution in shear of the CFRP increased. Other than that, spacing of the stirrups also play a main role, the larger the spacing of stirrups, the contribution of CFRP also is increased. The experimental result also indicated that the CFRP shear contribution to the shear capacity of the beam is strongly influenced by the presence of longitudinal rebar and vertical steel reinforcement in beam. When the presence of steel reinforcement decreased, the CFRP shear contribution to the shear capacity of beam increased. From the study, it is admitted that the externally bonded CFRP reinforcement to enhance capacity of the beam is considerable. Figure 2.5 shows the position of the strain gauges on the strengthened beam.

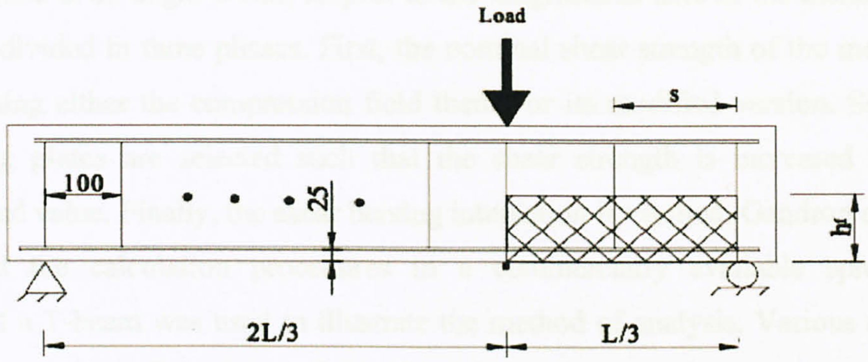


Figure 2.5: Position of the strain gauges on the strengthened beam.

Chajes et al. (1995) has tested beams reinforced externally with CFRP plates bonded to their soffit and sides to study flexural and shear behaviours. For the shear case, the fiber orientation was bonded only in the vertical direction of the beams. Chajes et al. believed that this orientation is the reason for the similarity in the applied load-deflection responses of flexural strengthened beams with and without external material where the vertical fiber had little effect on the flexural behavior of the beams. Unidirectional CFRP tow sheet having a dry thickness of 0.11 and a tensile modulus of elasticity of 227.37 GPa were used by Chajes et al. in that research.

From the testing, the continuous strips were able to control shear crack opening due to their greater axial stiffness, resulting in reduced shear deflection. This result showed that unlike the flexural soffit reinforcement, a thin sheet covering as much of the concrete as possible will not necessarily produce the greatest improvement in crack control where shear is concerned, but the sheet were able to avoid concrete shear failure where the failure mode was observed without the sheets. There was an increase in capacity of 115% stiffness, a change in failure mode from shear to flexure and an increase in ductility. By adding 2 single layer of CFRP sheet to the tensile face, a 292% increase in capacity and a 178% increase in stiffness were achieved.

On the analytical model, Gendron et al. (1999) presented an analytical model to predict the ultimate shear strength of reinforced concrete beams strengthened with fiber composite plates. The plates are added symmetrically on the lateral faces of the member and are inclined at an angle α with respect to the longitudinal axis of the member. The approach is divided in three phases. First, the nominal shear strength of the member is evaluated using either the compression field theory or its modified version. Secondly, strengthening plates are selected such that the shear strength is increased up to a predetermined value. Finally, the shear bendng interaction is verified. Gendron et al. has implemented the calculation procedures in a commercially available spreadsheet program and a T-beam was used to illustrate the method of analysis. Various analyses were performed with T-beam to show the effect of using different strengthening materials and inclination angles for the strengthening plates.

Chen and Teng (2001) agreed that strengthening of RC beams with CFRP show complex behavior. Although the failure mode and the shear strength of beams are affected by many factors, Chen and Teng assumed that the contribution of the steel stirrups and bent-up bars Vs and the contribution of concrete Vc are still fully developed so that they come out with the expression below to calculate the shear strength of a strengthened beam Vn,

$$\mathbf{V_n = V_c + V_s + V_{frp}}$$

where,
$\mathbf{V_n}$ is the shear strength of the strengthened beam
$\mathbf{V_c}$ is the shear contribution of concrete
$\mathbf{V_s}$ is the shear contribution of steel
$\mathbf{V_{frp}}$ is the shear contribution of fiber reinforced polymer

For this assumption to be valid for RC beams strengthened with non-prestressed FRP, a limit needs to be imposed on the usable ultimate strain so that the interlocking of aggregate remains effective at the ultimate limit state. It is stated that the level of prestress should at least be sufficient to enable full utilization of the tensile strength of FRP but should not be overly high so that the contribution of the internal steel shear reinforcement is fully mobilized when the FRP ruptures.

Regarding the test by using CFRP bars as the prestressing material, Ashour and Family (2006) have tested three flanged and two rectangular cross-section concrete beams reinforced with CFRP bars and compared with a companion concrete flanged beam reinforced with steel bars. There are several findings revealed from this testing such as the crack width in reinforced concrete flanged beam was greater than the companion steel reinforced concrete flanged beam. Other than that, flanged beams showed stiffer behaviour and higher load capacity than rectangular beams when the amount of CFRP reinforcement and depth are the same.

Other than that, Ashour et al. (2002) have studied the effect of CFRP on strengthening continuous beams. By analyzing and comparing three beams which were strengthened using different arrangement of CFRP plate reinforcement and one beam which was strengthened with CFRP sheets to a control beam, they has come out with several conclusions. One of it is that the load and moment capacities of the beam which is strengthened were increased by 55% to 57% but the problem is that the ductility of the strengthened beam is affected. Other than that, there is no significant difference found by them on the performance shown by the strengthened beams either it is strengthened with CFRP plates or CFRP sheets.

Ilki and Kumbasar (2001) has done testing on 10 specimens which is nearly the original size under the effects of constant axial load and reversed cyclic flexure to study the behavior of RC members that are repaired or strengthened by using CFRP. 9 of these damaged specimens are then strengthened by using CFRP composites in longitudinal and transverse directions before again being subjected to similar loading pattern as the original specimens. According to the test result, it is concluded that the behavior of strengthened specimens is improved in terms of strength, deformability, stiffness and energy dissipation capacity. Longitudinal fibers contributed to the strength of the RC member in the elastic range while the transverse fibers contributed to the deformability and strength of the member until the end of loading.

On the effect of temperature on RC elements strengthened with CFRP, Aguiar et al. (2008) has tested CFRP strengthened RC and control RC specimens to compressive shear and bending tests. They have found out that the epoxy adhesives exhibits poor behavior when subjected to increase temperatures which cause bond deterioration. From the shear test result, a rapid loss of resistant was apparent when cyclic thermal degradation increased above 60°C while the flexural strength capacity decreased with the increase of temperature and the efficiency of the CFRP strengthening tend to be negligible. Based on the results, Aguiar et al. conclude that the epoxy adhesive bond deteriorates quickly with the exposure to high temperature. This is important to be noted because even in normal solar exposure, the temperature can be high enough to cause deterioration, even at a little degree. Thus the choosing of epoxy must be done carefully to ensure that it can sustain the difference in temperature based on the location it will be used. Figure 2.6 shows the schematic of the compressive shear test while Figure 2.7 shows the three point bending test ran by Aguiar et al. for that research.

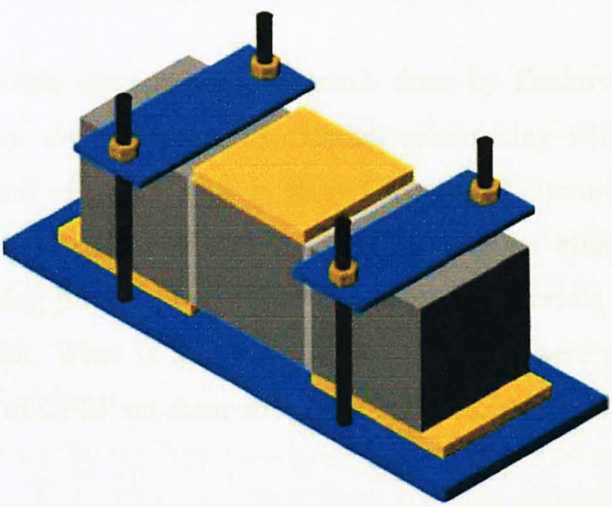


Figure 2.6: Schematic of the compressive shear test.

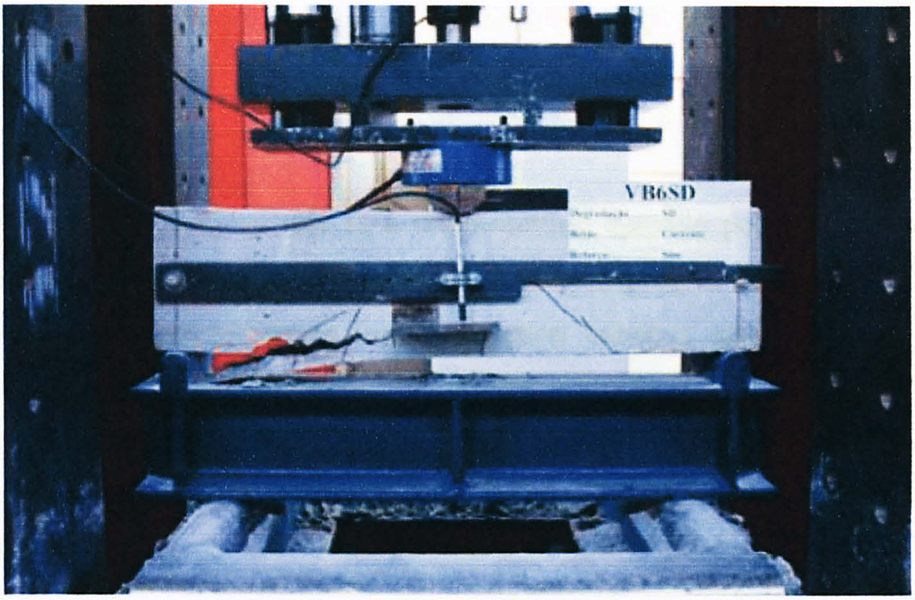


Figure 2.7: Three point bending test.

In terms of the effect of CFRP bars as prestressing material in continuous concrete beams, Ashour and Nageeb (2008) has reported that the increasing of CFRP reinforcement of the bottom layer concrete beam will enhance the load capacity and control deflection, while the increasing of top layer CFRP reinforcement will slightly reduce deflection of the beam but did not provide any improvement on load capacity.

Discussing on economic consideration, research done by Deskovic and Triantafillou (1991) which analyze the utilization of external prestressing with composites plates noted that this method of prestressing is more economical alternative to conventional prestressing method used in construction. These research on effect of CFRP towards structural strengthening justified that CFRP is a reliable materials to replace steel as a strengthening material. What is important is that to relate these available theories to determine the effect of CFRP on shear strengthening of skew beams.

2.4 Epoxy

2.4.1 History

In chemistry, epoxy or polyepoxide is a thermosetting epoxide polymer that cures (polymerizes and crosslinks) when mixed with a catalyzing agent or hardener. Most common epoxy resins are produced from a reaction between epichlorohydrin and bisphenol-A. The first commercial attempts to prepare resins from epichlorohydrin were made in 1927 in the United States. Credit for the first synthesis of bisphenol-A-based epoxy resins is shared by Dr. Pierre Castan of Switzerland and Dr. S.O. Greenlee of the United States in 1936.

Dr. Castan's work was licensed by Ciba, Ltd. of Switzerland, which went on to become one of the three major epoxy resin producers worldwide. Ciba's epoxy business was spun off and later sold in the late 1990s and is now the advanced materials business unit of Huntsman Corporation of the United States. Dr. Greenlee's work was for the firm of Devoe-Reynolds of the United States. Devoe-Reynolds, which was active in the early days of the epoxy resin industry, was sold to Shell Chemical. Shell Chemical now known as Hexion.

The applications for epoxy-based materials are extensive and include coatings, adhesives and composite materials such as those using carbon fiber and fiberglass reinforcements although polyester, vinyl ester, and other thermosetting resins are also used for glass-reinforced plastic. The chemistry of epoxies and the range of commercially available variations allow cure polymers to be produced with a very broad range of properties. In general, epoxies are known for their excellent adhesion, chemical and heat resistance, good-to-excellent mechanical properties and very good electrical insulating properties. Many properties of epoxies can be modified for example silver-filled epoxies with good electrical conductivity are available, although epoxies are typically electrically insulating. Variations offering high thermal insulation, or thermal conductivity combined with high electrical resistance for electronics applications are now available.

2.4.2 Epoxy as adhesives

Talking about wrapping the skew beams with CFRP strips, the need for epoxy as a reliable adhesive material are very crucial. Epoxy adhesives are a major part of the class of adhesives called "structural adhesives" or "engineering adhesives" which also includes polyurethane, acrylic, cyanoacrylate, and other chemistries. These high-performance adhesives are used in the construction of aircraft, automobiles, bicycles, boats, golf clubs, skis, snow boards, and other applications where high strength bonds are required. Epoxy adhesives can be developed to suit almost any application. They are exceptional adhesives for wood, metal, glass, stone, and some plastics.

Epoxy adhesives can be made flexible or rigid, transparent or opaque/colored, fast setting or extremely slow setting. Epoxy adhesives are almost unmatched in heat and chemical resistance among common adhesives. In general, epoxy adhesives cured with heat will be more heat- and chemical-resistant than those cured at room temperature. The strength of epoxy adhesives is degraded at temperatures above 350°F. Some epoxies are cured by exposure to ultraviolet light. Such epoxies are commonly used in optics, fiber optics, optoelectronics and dentistry.

Hutchinson and May (1992) in their journal has summarized the advantages of epoxy resins over other polymers as adhesive agents for civil engineering use. One of it is that it have high surface activity and good wetting properties for a variety of substrates, it also may be formulated to have a long open time which is the time spend between mixing and closing of the joint. Epoxy resins also have high cured strength where the joint failure may be dictated by the adherend strength particularly with concrete substrates. This type of epoxy suffers minimal shrinkage on curing, low creep and superior strength retention under sustained load.

These advantages of epoxy are contributed by the modifications done which at the same time make it relatively expensive in comparison to other adhesives. However, the toughness, range of viscosity and curing conditions, good handling characteristics, high adhesive strength, inertness, low shrinkage and resistance to chemicals meant that epoxy adhesives can be applied in many applications in construction industry.

A number of researches have been done on the testing of adhesive. However, appropriate tests for assessing bond strength are complicated by the fact that the loading condition in service is difficult to simulate, and concrete tends to be weaker in tension and shear than the adhesives which may be used. Hollaway et al. (1995) , in their journal have reported a programme of small scale tests to investigate three different adhesives, two of which were two part cold cure epoxies and the third is a part acrylic.

Several test has been conducted such as which subjecting an adhesive or concrete joint to tensile force and a composite/adhesive/concrete joints to shear, to verify the adequacy of the surface preparation of the concrete and composite bond surfaces. In these tests, the Sikadur 31 PBA epoxy adhesive was superior to the other two products and demonstrated strengths in both tension and shear which exceeded those of the concrete.

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 Project Workflow and Identification

The whole project was conducted through several steps. First in the planning step, all the workflow were determined and organized to well fit in the Final Year Project (FYP) time frame. This is important to ensure smooth running of the project. To ensure that the work can be done effectively, Gantt charts as shown in *Appendix 1-1 and 1-2* were prepared.

Then several research and study were conducted on related topics to increase the knowledge through data mining process. Parallel to this step, a few visits and preliminary works were carried out at the concrete lab to be familiar with the materials, equipments and tools utilized throughout the project. There are two major equipments involved in this research project which is 500 kN Dynamic Machine for the static load test of the beams and also 3000 kN Compression Machine for the compressive strength test of the concrete test cubes.

After the targets have been set to achieve the objectives, the designing process and lab works were conducted as being planned in the Gantt chart to fit the FYP time frame. There are many laboratory works done mainly at the concrete lab such as erection of formwork, installation of reinforcement bars and links, casting of beams, preparation of epoxy and followed by the attachment process of CFRP strips. Safety precautions were followed throughout the lab works to avoid injuries and at the same time, advice on the correct construction practice were seek from qualified personnel such as lab technologist and Post Graduate (PG) Researchers to avoid structural failure due to construction faults or poor construction practice from happens.

Finally, after all the curing period of beams and curing period of external CFRP-epoxy-concrete are achieved, the testing of beam were conducted using Dynamic Machine 500kN to determine the ultimate force that can be sustained by the skew beams before failed. Thus the effect of CFRP can be analyzed and justified. The summary of the project flow and identification are shown in *Figure 3.1*.

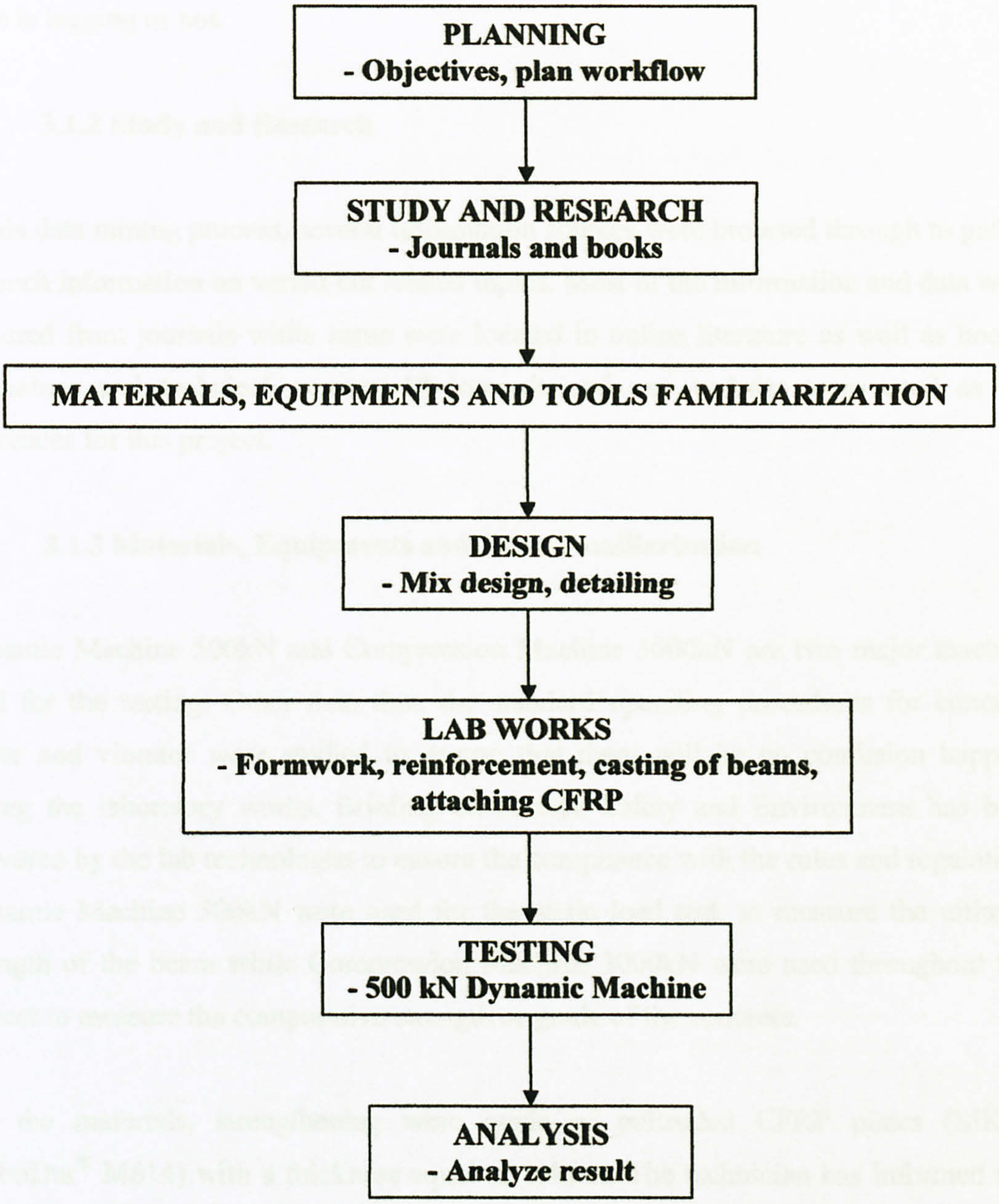


Figure 3.1: Project Workflow and Methodology

3.1.1 Planning

Planning has been conducted during the first two weeks of the semester January 2009. In this step, several process identification and organization were held with help from supervisor to fit all the process well in the FYP time frame. The Gantt chart was drafted to make sure that any progress can be coordinated with the planning to identify whether there is lagging or not.

3.1.2 Study and Research

In this data mining process, several information sources were browsed through to gather as much information on varied but related topics. Most of the information and data were gathered from journals while some were located in online literature as well as books, magazines and technical reports. 18 journals and one website were used as the references for this project.

3.1.3 Materials, Equipments and Tools Familiarization

Dynamic Machine 500kN and Compression Machine 3000kN are two major machine used for the testing. Other than that, the standard operating procedures for concrete mixer and vibrator were studied to ensure that there will be no confusion happens during the laboratory works. Briefing on Health, Safety and Environment has been delivered by the lab technologist to ensure the compliance with the rules and regulation. Dynamic Machine 500kN were used for the static load test, to measure the ultimate strength of the beam while Compression Machine 3000kN were used throughout this project to measure the compressive strength or grade of the concrete.

For the materials, strengthening were made of pultruded CFRP plates (SIKA® CarboDur® M614) with a thickness equal to 1.4mm. The technician has informed that the nominal values of the Young's modulus and the tensile strength are greater than 200GPa and 2800 MPa respectively. The Poisson's ratio of the overlays was assumed equals to 0.3 and the tensile strain is 0.008. For the adhesive, epoxies can be formulated to have excellent chemical resistance and have a low propensity for the absorption of moisture. A commercially available Sikadur® -30 epoxy adhesive from SIKA was used, which is a two-component system (an epoxy resin and a hardening agent). This epoxy is a thixotropic adhesive mortar based on a 2-component solvent free epoxy resin. The adhesive properties provided in Table 3.1 are according to manufacturer's specification.

Table 3.1: Technical data and properties of Sikadur-30 epoxy adhesive

Items	Details
Color	Base (Part A) : White Hardener (Part B) : Black Part A + B : Light grey when mixed
Mix ratio	A : B = 3 : 1 (parts by weight & volume)
Density	1.65 kg/L ± 0.1 kg/L (A + B) at 23°C
Shelf life Pot life Open time	24 months from date of production 40 minutes (at 35°C) 30 minutes (at 35°C)
Sag flow	3 – 5 mm (at 35°C)
Shrinkage	0.04 %
Glass transition temperature	+62°C
Static modulus of elasticity	11200 MPa
Application thickness	Up to 10 mm
Application temperature	+8°C to +35°C
Compressive strength	90 MPa
Tensile strength	30 MPa
Shear strength	15 MPa
Bond strength (on steel)	> 21 MPa on correctly prepared surface
Maximum Service Temperature	+50°C
Coefficient of Thermal Expansion	$9x10^{-5}$/°C (-10°C to +40°C)
Adhesive Strength	Steel 33 MPa (sandblasted substrate)

3.1.4 Design

In the design process, the number and sizing of skew beam required for this project are determined with the advice from supervisor. At the early stage of this project, it has been decided that six beams with the sizing of 100mm x 150mm x 2000mm will be casted for the testing. However, after some discussion and laboratory works has been done, in week 10, it is decided that the beam sizing that should be casted is changed to 150mm x 230mm x 2000mm.

These changes in cross-sectional area become compulsory because it is not feasible to bend the links for a small size beam with 100mm x 150mm cross-sectional area which might affect the final result. The other reason is that that size of beam is too small to be tested in imagination of a bridge beam. In terms of aggregates size, only 20mm aggregates available at the UTP laboratory so it is not feasible to use this size of aggregate for a 100mm x 150mm x 2000m beams. With a small cover and big size of aggregates, the aggregates may be clogged up between the reinforcement bars and formwork which can block the flow of the fresh concrete thus results into honey comb and porosity. Figure 3.2 below show the cross-sectional area of the proposed beam before and after changes.

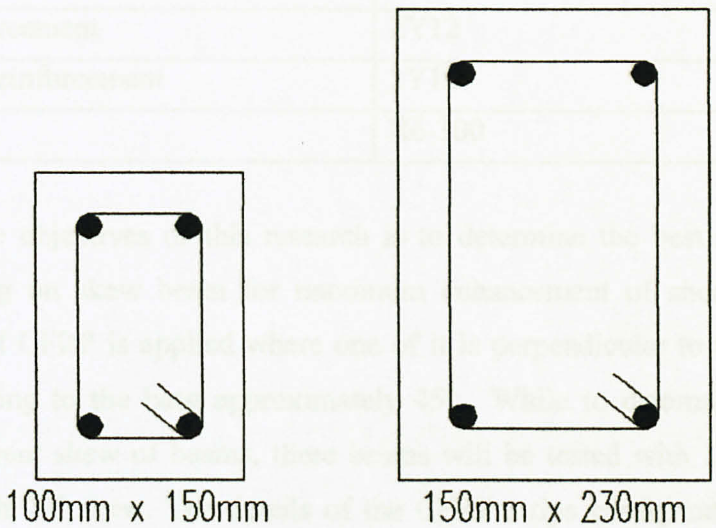


Figure 3.2: Cross-sectional area of the proposed beam

For the material properties, the beams were casted using Ordinary Portland Cement (OPC) with a maximum of 20mm aggregate size. In terms of strength, as normally for a bridge or a flyover, a high grade of concrete is used compared to the normal Grade 25 used for building, concrete with a target 28-days compressive strength of 35 N/mm^2 were used for this research work. For each batch of concrete mixing done to cast the test beams, three 100mm x 100mm x 100mm cubes were prepared and tested to ensure that it reach the target strength. For a grade 35 concrete, it has been computed that the water:cement:sand:aggregate ratio will be 0.5:1:2.4:3.5. To ensure that the beams fail in shear, the nominal shear reinforcement were used where 6mm mild steel stirrups were installed with 300mm spacing interval considered center to center. Table 3.2 shows the final characteristic decided for the concrete test beam.

Table 3.2: Characteristics for the concrete test beam

Item	Characteristic
Dimension	150mm x 230mm x 2000mm
Cement Type	Ordinary Portland Cement
Aggregate size	20mm
Water cement ratio	0.5
Concrete grade	35
Cover	25mm
Tension reinforcement	2Y12
Compression reinforcement	2Y12
Stirrups	R6-300

Considering the objectives of this research is to determine the best configuration of CFRP wrapping on skew beam for maximum enhancement of shear capacity, two configuration of CFRP is applied where one of it is perpendicular to the base and the other one slanting to the base approximately 45°. While to determine the effect of CFRP on different skew of beams, three beams will be tested with 15° skew and the other three with 20° skew. The details of the CFRP strips configuration is shown in Figure 3.3 while the plan view of the beam arrangement on the support which shows the skew of beam is shown in Figure 3.4.

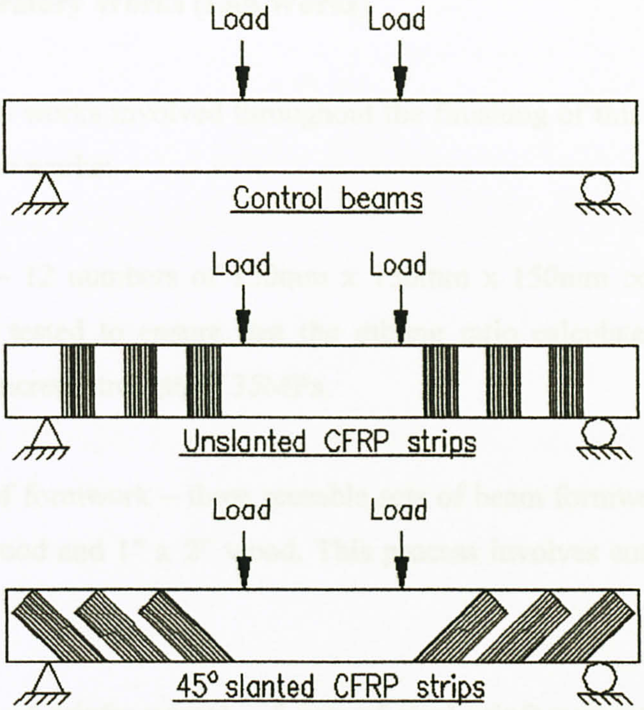


Figure 3.3: Configuration of CFRP strips

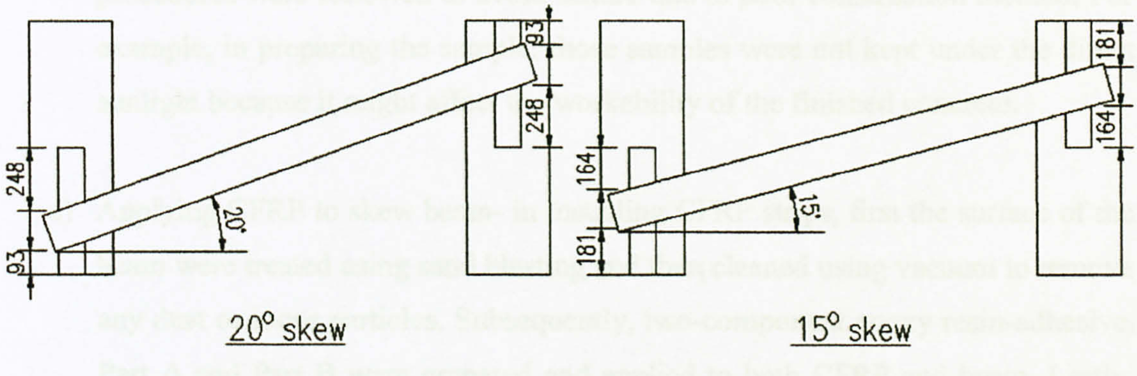


Figure 3.4: Plan view of beam arrangement during testing

3.1.5 Laboratory Works (Lab Works)

There are many lab works involved throughout the finishing of this project. Below are the details of the lab works:

a) Trial mix – 12 numbers of 150mm x 150mm x 150mm concrete cubes were casted and tested to ensure that the mixing ratio calculated can produce the required concrete strength of 35MPa.

b) Erections of formwork – three reusable sets of beam formwork were fabricated using plywood and 1" x 2" wood. This process involves cutting and nailing of woods.

c) Installation of reinforcement – 6 sets of steel reinforcement using 12mm high yield steel bars as the main bar and 6mm mild steel bars as the stirrups. This process involves cutting, bending and tying of the steel bars and stirrups.

d) Concrete mixing and casting of beams – 6 sets of mixing for casting of 6 numbers of concrete beams. In preparing the mixing and do casting, some procedures were followed to avoid failure due to poor construction method. For example, in preparing the sample, those samples were not kept under the direct sunlight because it might affect the workability of the finished concrete.

e) Applying CFRP to skew beam- in installing CFRP strips, first the surface of the beam were treated using sand blasting and then cleaned using vacuum to remove any dust or loose particles. Subsequently, two-component epoxy resin-adhesive, Part A and Part B were prepared and applied to both CFRP and beam. Lastly, the CFRP strips were placed immediately on the concrete substrate and pressed with rubber roller to ensure good contact between the epoxy, the concrete and the CFRP.

3.1.6 Testing

After attaching the CFRP strips, the complete application was subsequently left to cure for at least 24 hours before the testing. Static load test were done using 500 kN Dynamic Machine to know the ultimate strength of all the 6 test beams.

3.1.7 Analysis

The graph of *Applied Load vs Beam Deflection* were worked out using the data obtained from the static load test. The results were analyzed to know the effect of CFRP strips in strengthening skew beams.

CHAPTER 4

RESULTS AND DISCUSSIONS

Before the beam is casted, trial mix has been done two times to ensure that the right proportion of materials is used in getting grade 35 concrete. The first trial mix failed as it is too dry and not workable. From the discussion with the lab technologists, it is agreed that the reason is that the cement, sand and aggregate which is already weighed is kept under the direct sunlight for hours before the mixing is begun. This condition make those samples become too dry and absorb water provided thus reduce the water cement ratio. Added by the heat, the characteristics of cements changed thus it is not mixed homogenously which resulted into too dry and not workable fresh concrete.

For the second set of trial mix, again, 12 concrete cubes with 150mm x 150mm x 150mm size were casted. 3 of the cubes is tested for a 3-days compressive strength, the other 3 of the cubes is tested for 7-days compressive strength while the last 6 of the cubes is tested for 28-days compressive strength. *Figure 4.1* below shows one of the samples which experience cracks under compression at 28 days.

Figure 4.1: Concrete cube failed under compression

From the results obtain from the compressive test, the characteristic value of the concrete can be determined by using this formula:

$$\mathbf{f_k = f_m - 1.64\ s}$$

where:
$\mathbf{f_k}$ is the characteristic value
$\mathbf{f_m}$ is the mean value – normally determined from cubes which are tested 28 days after casting
s is the standard deviation of the results

By following this calculation, the characteristics strength obtained for that trial mix is conformed to be 35.621 N/mm^2. In the design code (BS 8110), concrete is graded according to the characteristic compressive strength and designated as: C30, C35, C40 where the number 30, 35 and 40 represent the compressive strength in N/mm^2. So that, from this trial mix results and the calculation of characteristic strength, it is shown that the grade for this concrete can be classified as C35 which satisfied the design requirement for this project.

To obtain the grade C35 concrete, all the 6 beams were casted with the same mixing ratio of water:cement:sand:aggregate at 0.5:1:2.4:3.5. As the concrete mixer available in the UTP laboratory is too small, two mix need to be set up for each beam and for each beam casted, three 100mm x 100mm x 100mm concrete cubes were prepared. Those cubes were tested using 3000 kN compression machine and the result is shown in Table 4.1 in Page 31.

The same formula used in determining the characteristics strength for trial mix is applied for these cubes. Taken 'fm' as the mean value and 's' as the standard deviation, the 'fk' or the characteristics strength for each beam is also shown in Table 4.1. From the results obtained for each beam, beam 1 has recorded characteristics strength of 34.83 MPa, beam 2 with 35.03 MPa, beam 3 with 35.04 MPa, beam 4 with 34.25 MPa, beam 5 with 36.98 MPa and the last one, beam 6 with 34.78 MPa. Taking the C35 meaning the characteristics strength of the beam is 35.00 MPa, all the beams can be considered as meeting the requirement with the maximum variation of 5.66%. Usually in construction, a variation up to 20% is allowable. The maximum variation is considered by taking the difference between the values with largest difference to 35 MPa, divided by the required value of 35 MPa.

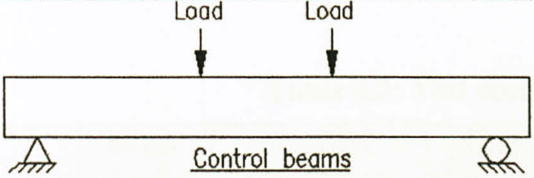
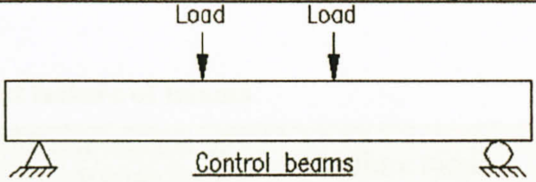
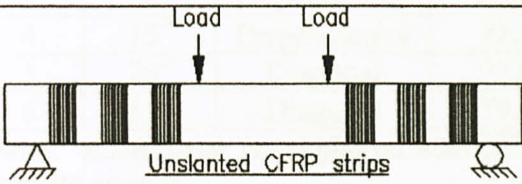
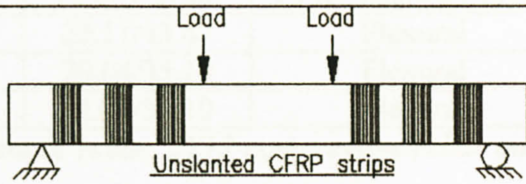
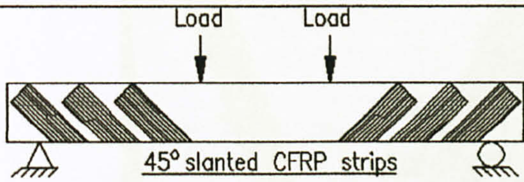
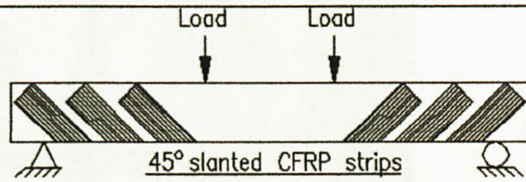
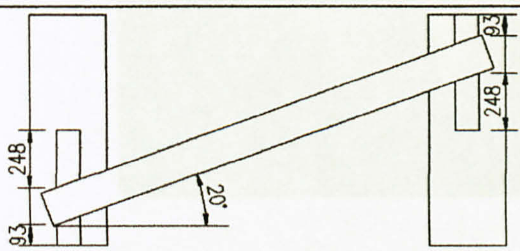
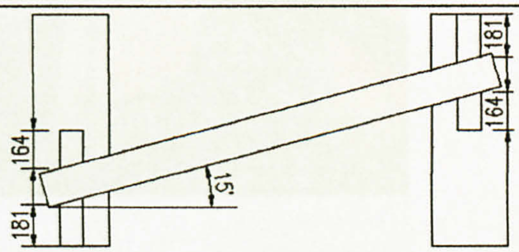
Variation = (36.98 MPa – 35.00 MPa) / 35.00 MPa x 100%
= 5.66 %

Table 4.1: Compressive test result

Beam No.	Cube Sample	Max Load (N)	Compressive Strength (Mpa)	fm (Mpa)	s	fk (Mpa)
Beam 1	1a	36550000	36.55	36.68	1.13	34.83
	1b	37870000	37.87			
	1c	35620000	35.62			
Beam 2	2a	37160000	37.16	38.43	2.07	35.03
	2b	40810000	40.81			
	2c	37310000	37.31			
Beam 3	3a	39720000	39.72	37.81	1.69	35.04
	3b	36520000	36.52			
	3c	37190000	37.19			
Beam 4	4a	36660000	36.66	36.01	1.07	34.25
	4b	36590000	36.59			
	4c	34770000	34.77			
Beam 5	5a	37280000	37.28	37.96	0.6	36.98
	5b	38190000	38.19			
	5c	38410000	38.41			
Beam 6	6a	37190000	37.19	37.07	1.4	34.78
	6b	38410000	38.41			
	6c	35620000	35.62			

After satisfied with the cube compressive strength of the beams, 2 control beams were tested under the static load using 500 kN dynamic machine. As the mode of failure for both control beams are the same which is shear failure, the design can be considered as success. The other 4 beams are then strengthened with CFRP strips and after the bonding were left cured; they were tested using the same technique. The details of all the 6 beams and their testing were shown in Table 4.2 in Page 32.

Table 4.2: Details of beam and their testing

Beam Tested with 20° Skew Angle	Beam Tested with 15° Skew Angle
 Beam 1. *Control Beam*	 Beam 2. *Control Beam*
 Beam 3. *Beam with perpendicularly wrap CFRP*	 Beam 4. *Beam with perpendicularly wrap CFRP*
 Beam 5. *Beam with diagonally wrap CFRP*	 Beam 6. *Beam with diagonally wrap CFRP*
 Plan view of beam arrangement on support	 Plan view of beam arrangement on support

From the static load test using 500kN dynamic machine, Table 4.3 in Page 33 shows the results of all the 6 beams tested in terms of its ultimate force before failure, the contribution of CFRP and the failure mode. As being discussed by Chen and Teng in their journal, the increase of the ultimate load that can be sustained by the strengthened beam before failure compared to the ultimate load that can be sustained by the control beam is considered as contribution of CFRP.

Table 4.3: Test results at failure of beams

Beam	Skew Angle	CFRP Orientation	Ultimate force (kN)	Contribution of CFRP (kN/%)	Failure mode
1	20°	-	57.01	0	Shear
2	15°	-	57.77	0	Shear
3	20°	Perpendicular	69.03	12.02 / 21.08	CFRP peeling / Shear
4	15°	Perpendicular	82.88	25.11/43.47	Flexural
5	20°	Diagonal	77.05	20.04/35.15	Flexural
6	15°	Diagonal	79.78	22.01/38.10	Flexural

Note: *Each beam is reinforced with 2Y12 tensile rebar, 2Y12 compressive rebar and 300-R6 stirrups.*

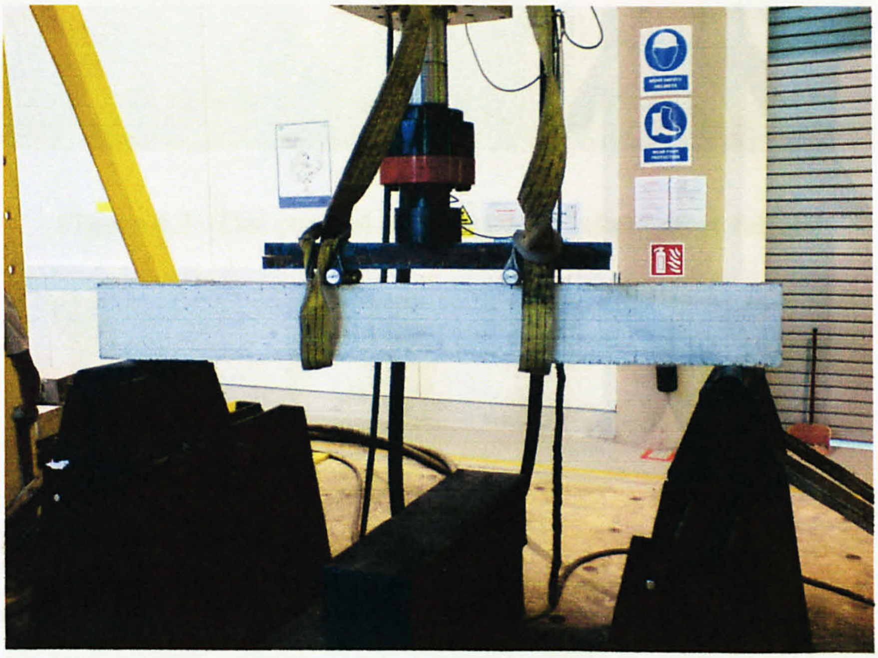


Figure 4.2: The control beam with 20° skew during static load test

Figure 4.2 shows Beam 1, the control beam during the static load test with 20° skew while Figure 4.3 in Page 34 shows the condition of that beam after failure. As being discussed by Bjorn Taljsten, the failure of this beam starts with combined bending and shear stresses that develop into shear crack. Beam 1 experienced shear failure where the maximum diagonal stresses occur near to its support. From Figure 4.3, it is clear that the angle of cracks for Beam 1 is about 45° which satisfy the criteria for shear failure.

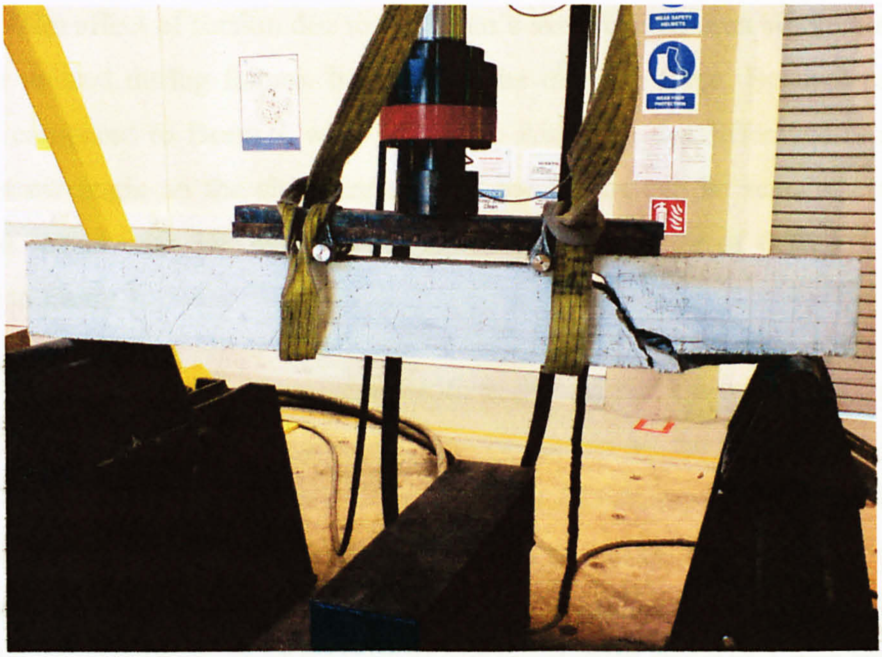


Figure 4.3: The control beam with 20° skew after failure

Figure 4.4: The control beam with 15° skew after failure

Figure 4.4 in Page 34 shows Beam 2, the control beam tested under static load test with 15° skew. Beam 2 undergo similar failure like the one faced by Beam 1. The failure of Beam 2 also occurs near to the right support however for this case, the angle of crack is about 50°. The effect of torsion due to the beam's skew can be seen where both control beams are twisted during failure. In terms of the ultimate force, Beam 2 can sustain 57.77 kN compared to Beam 1 with 57.01 kN. Although the difference is small, the effect of skew angle on the shear capacity of the beams can be seen where Beam 2 which was tested with 15° skew has a higher shear capacity of 0.76 kN or 1.33% compared to Beam 1.

For the Beam 3 which was strengthened with perpendicularly u-wrap CFRP and being test with 20° skew, the ultimate load that can be sustain by the beam before failure is 69.03kN, there is an increase in strength of about 21.08% compared to its control beam. For this beam, although there are significant cracks at tensile region, however suddenly 3 CFRP strips peeled off and an abrupt shear failure take place at both supports. This failure might happen because the epoxy is not cured well; this beam was cured inside the laboratory so maybe the cold temperature affects the curing process compared to the other beams which are cured outside the lab. The failed Beam 3 is shown in Figure 4.5.

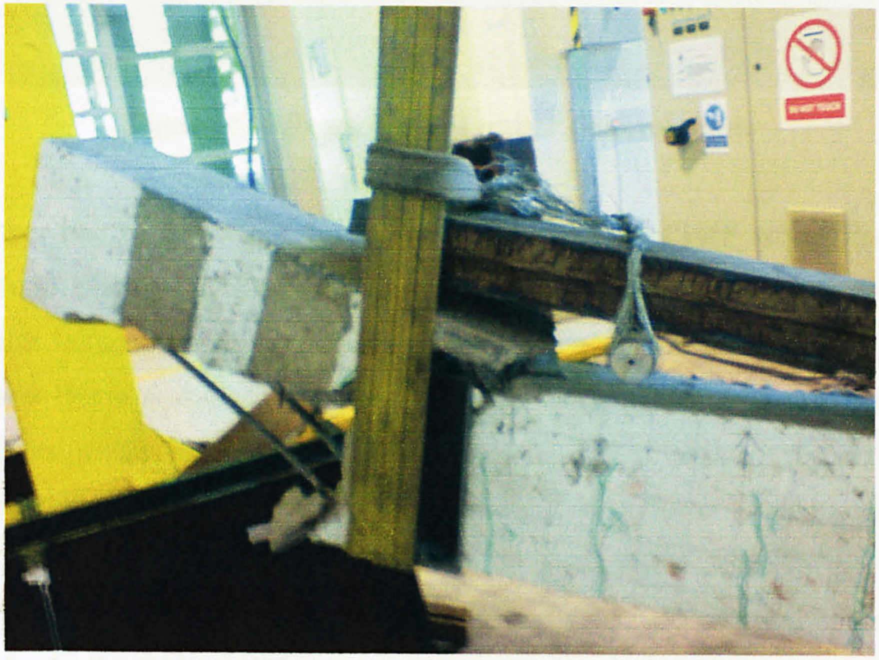


Figure 4.5: Peeling of CFRP and shear failure of Beam 3

Figure 4.6 shows the failure of Beam 4, which is perpendicularly u-wrap with CFRP strips and tested under static load with 15° skew. The ultimate force that can be sustained by this beam is 82.88 kN which is a 43.47% increase in strength compared to its control beam. This result demonstrates that CFRP strips can strengthen the beam in shear thus make it failed by flexural. The increase of more than 40% strength proved that the shear strengthening technique using CFRP is very effective and at the same time the hazardous brittle failure due to shear can be avoided.

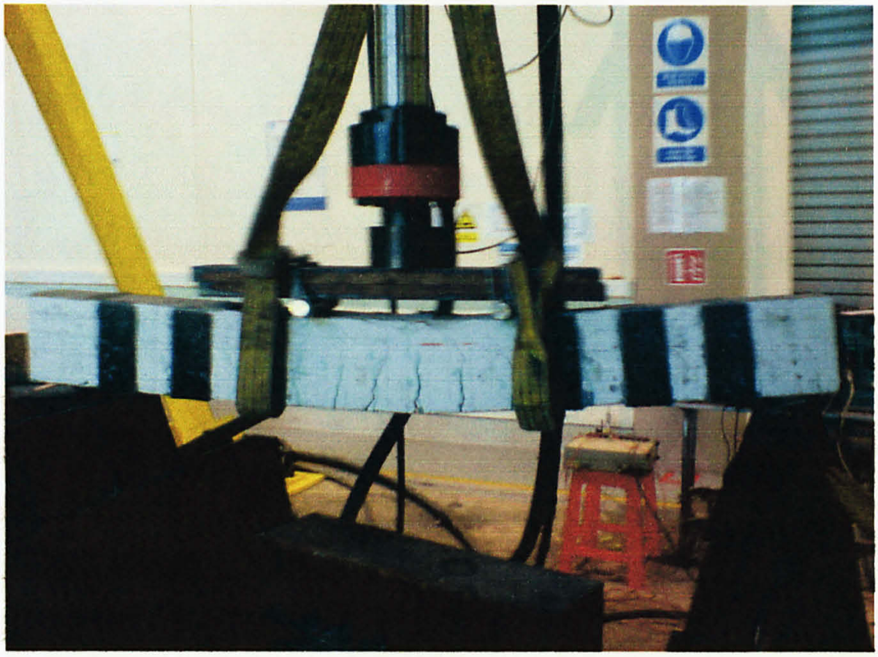


Figure 4.6: Beam 4 failed under flexural mode

For the other two beams which is diagonally u-wrap with CFRP strips, Beam 5 was tested with 20° skew while Beam 6 was tested with 15° skew. Both beams demonstrate quite similar failure mode where it is due to the bending at the middle of the beam. Beam 5 and Beam 6 can sustain 77.05 kN and 79.78 kN applied load respectively before it failed, this is an increase of 35.15% and 38.10% of strength respectively. The results show that the 15° skewed beam has a 2.95% better strengthening effect compared to the 20° skewed beam. For the control beam, Beam 2, the 15° skewed beam shows an advantage of 1.33% in strength compared to the 20° skewed control beams, Beam 1. Basically this condition proved that the skew angle play an effect on the strength of the skew beams with a difference of 1.33% for control beam and 2.95% for strengthened beam. To visualize the failure condition of Beam 5 and Beam 6, Figure 4.7 and Figure 4.8 shows the condition of Beam 5 and Beam 6 after failure respectively.

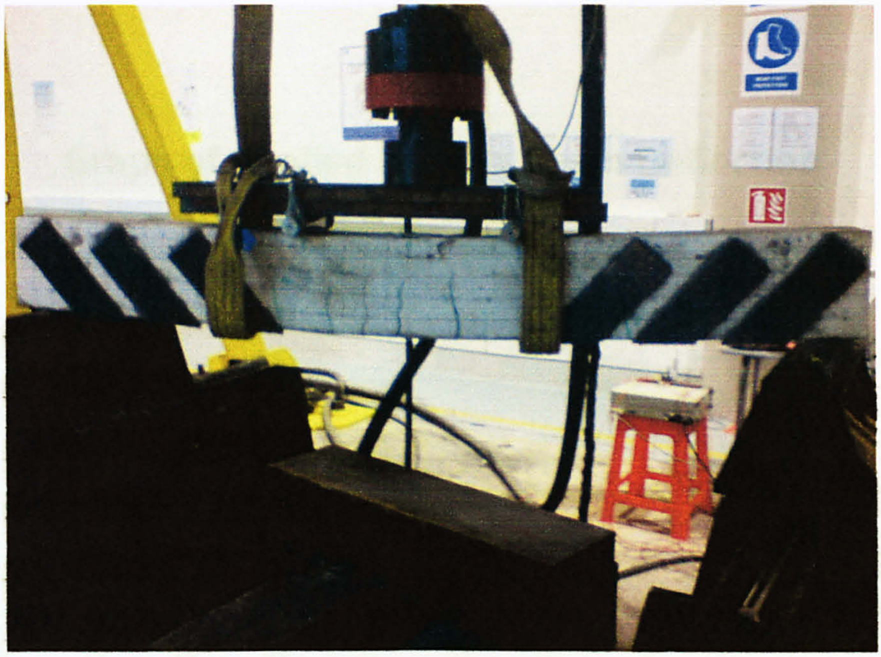


Figure 4.7: Beam 5 failed under flexural mode

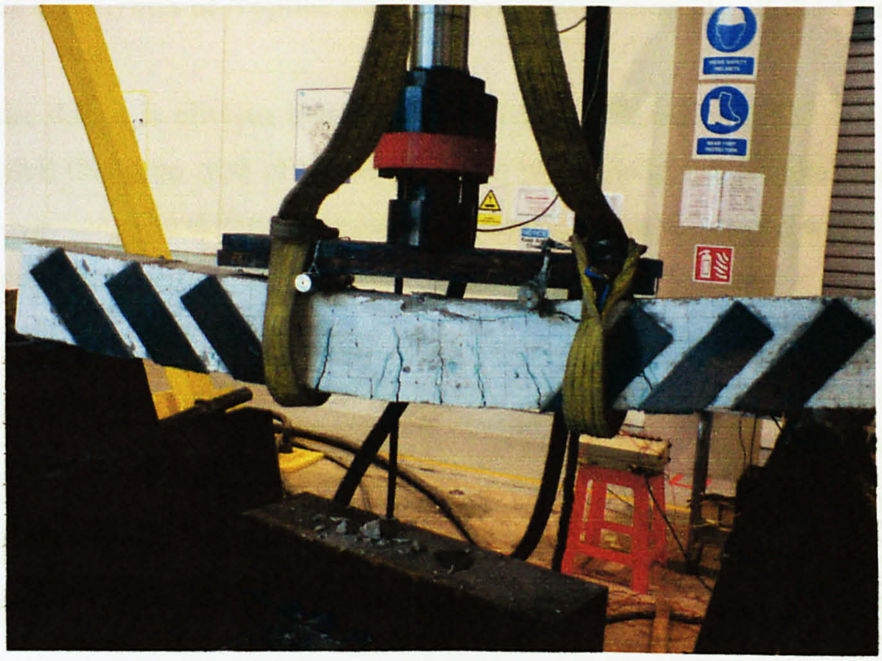


Figure 4.8: Beam 6 failed under flexural mode

To get a better view on the comparison between all the 6 beams, Figure 4.9 shows the graph of Applied Load vs Beam Deflection which was prepared according to the data obtained from the static load test. In addition to that, the raw data for Beam 4, the perpendicularly wrapped beams which was tested with 15° skew are shown in Appendix 2-1.

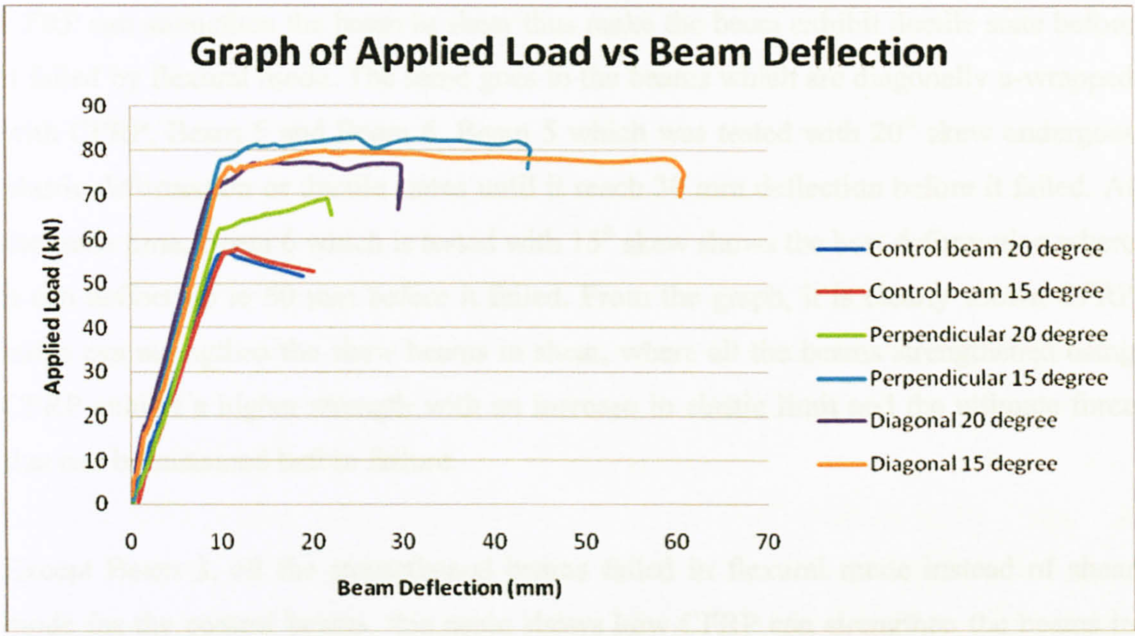


Figure 4.9: Graph of Applied Load vs Beam Deflection for all the 6 beams

From Figure 4.9, it is obvious that both control beams tested with 15° and 20° skew angles exhibit the same type of failure which is shear mode and a quite similar load-deflection reaction. The difference is just that Beam 2 which was tested with 15° exhibit a higher strength capacity of about 1.33% compared to Beam 1.

According to the graph, the third beam which is wrapped perpendicularly and tested with 20° skew shows that it can handle higher strength, but after about 10mm deflection, one of its CFRP strips was peeled off. That peeled off affects the elasticity of the beam, then suddenly when the applied load reach 69.03 kN, the other two CFRP strips were peeled off make an abrupt shear failure occur at both support. From this graph, it can be imagine that if there is no debonding of CFRP strips, Beam 3 might shows better strength development which is close to the one demonstrated by Beam 4.

For Beam 4, the beam which is wrapped perpendicularly and tested with 20° skew, when compared to the control beam, undoubtedly it has a higher elasticity, higher elastic limit and improves in ductility. From here it is very clear that this arrangement of CFRP can strengthen the beam in shear thus make the beam exhibit ductile state before it failed by flexural mode. The same goes to the beams which are diagonally u-wrapped with CFRP, Beam 5 and Beam 6. Beam 5 which was tested with 20° skew undergoes plastic deformation or ductile states until it reach 30 mm deflection before it failed. At the same time, Beam 6 which is tested with 15° skew shows the best deformation where it can deflect up to 60 mm before it failed. From the graph, it is clearly shown CFRP strips can strengthen the skew beams in shear, where all the beams strengthened using CFRP exhibit a higher strength with an increase in elastic limit and the ultimate force that can be sustained before failure.

Except Beam 3, all the strengthened beams failed in flexural mode instead of shear mode for the control beams, this again shows how CFRP can strengthen the beams in shear. Beam 3 as being discussed before failed due to the peeling of CFRP strips, most probably because the epoxy is not cured well, so if there is no CFRP peeling, it is believed that Beam 3 also will fail in flexural mode. According to the epoxy supplier, the epoxy should be cured 14 days to reach its maximum shear strength which is about 17-20 N/mm^2, however a minimum of 24 hours curing are allowed as after that long, the epoxy already reach about 90% performance. However, the 24 hours curing time only applicable if it is cured in about 35°C temperature. So for Beam 3, although it is cured about 48 hours but as it is cured inside the laboratory with air-conditioning system, the curing process of it might be affected.

In terms of the effect of skew angle on strength, both strengthened beams tested with 15° skewed, Beam 4 and Beam 6 exhibits the highest resistance to applied load with 82.88 kN and 79.78 kN respectively. Continued by both strengthened beams tested with

20° skewed, Beam 5 and Beam 3 with 77.05 kN and 69.03 kN respectively. Although the difference is not that high but from the results, the skew angle still take effect in the strength of the beams. Beams tested with 15° skew have a higher strength compared to the beams tested with 20° skew. This can be explained where when the skew angle is bigger the torsional force exerted to the beam also increased and make the beam prone to rotate or twisted. This torsional force act as an imaginary applied load to the beams which make the skew beams failed at a lower applied load.

For the effect of CFRP wrapping configuration on skew beam, Beam 4, the perpendicularly wrapped beam with 15° skew have a highest strength where it can sustain up to 82.88 kN ultimate load before it failed compared to Beam 6, the diagonally wrapped beam with 15° skew which can sustain 79.78 kN. The difference of about 3.1 kN or 3.89% provide evidence that perpendicularly wrapped beams can provide a higher strengthening effect compared to the diagonally wrapped beams. However, in terms of deflection, Beam 4 only allowed the deflection of about 40mm before it failed compared to Beam 6 which allowed the deflection of up to 60mm. For this case, Beam 3 and its partner, Beam 5 which is also tested with 20° skew are not considered for this discussion as Beam 3 failed in an unexpected condition mainly due to the poor curing technique.

To get a better view on how the perpendicularly wrapped CFRP contribute more to the shear capacity while the diagonally wrapped CFRP contribute more to the deflection of the beam, Figure 4.10 and Figure 4.11 shows the CFRP configuration for Beam 4 and Beam 6.

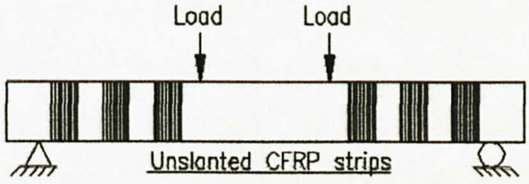


Figure 4.10: CFRP configuration for Beam 4

As shown in Figure 4.10 in Page 40, the perpendicularly wrapped CFRP will provide higher resistance to the force exerted from top of the beam but at the same time due to its configuration, it will reduce the deflection of the beam. While as exposed in Figure 4.11, the diagonally wrap CFRP configuration tend to allow more deflection to the beam but at the same time, due to its arrangement which is inclined and its unidirectional CFRP layer, it is not that tough in handling the exerted forces from the top of the beam.

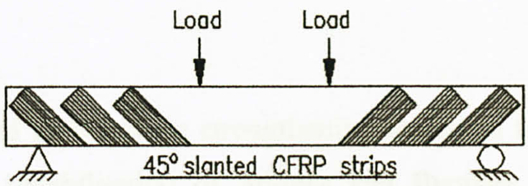


Figure 4.11: CFRP configuration for Beam 6

From the discussions, it is clear that skew angle of the beam and CFRP configuration both play effect on the strength and the strengthening of the beams.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

CFRP have the potential as the shear strengthening materials for skew beam which is mainly related to the rehabilitation of bridges and flyovers. CFRP offer excellent corrosion resistance to environmental agents as well as the advantages of high stiffness-to-weight and strength-to-weight ratios when compared to the conventional construction materials which has been discussed in Chapter 2. Perhaps the biggest advantage of CFRP is tailorability where the strengthening can be arranged easily according to loading conditions so that it can be optimized for performance. The apparent high cost of CFRP compared to conventional materials can be neglected when considering the costs comparison due to transportation, installation and life cycle costs where CFRP needs less maintenance compared to the conventional method.

From this project, it is proved that CFRP strips can be used as an alternative for shear strengthening of skew RC beams. All the four beams strengthened with CFRP shows an increase in strength where there is a significant increase in the ability of the beams to sustain the exerted forces in the range of 21.08% up to 43.47%. By neglecting Beam 3 which is failed in shear after three of its CFRP strips peeled off, it can be conclude that all the strengthened beams are failed in flexural mode compared to the control beams which failed in shear mode. This statement can be considered as fact if the peeling of CFRP for Beam 3 is really happens due to a poor curing process. If it is factual, then the minimum strengthening contribution of CFRP strips is above 35% which can be considered as efficient.

Seeing one the objective of this study is to find out the best configuration of CFRP wrapping on skew RC beam for maximum enhancement of beam shear capacity, by comparing Beam 4 and Beam 6, it is obvious that perpendicularly wrapped CFRP increase the shear capacity more compared to the diagonally wrapped. So in this case, it can be conclude that perpendicularly wrapped CFRP will improve the strength better. For this case, Beam 3 and Beam 5 are out of comparison because Beam 3 is failed in shear mode mainly because of the poor curing of epoxy which trigger the peeling of CFRP.

For the second objectives which is to study the effect of skew angle on the strengthening, both beams experience the strengthening effect, however from the results, it is clear that beams tested with 15° skew demonstrate a higher strengthening effect. From the results, beams tested with 15° skew, Beam 4 and Beam 6 exhibit a higher strength with the ability to sustain the applied load of 82.88 kN and 79.78 kN respectively compared to its counterpart, Beam 3 and 5 which were tested with 20° skew with 69.03 kN and 77.05 kN respectively. These results demonstrate that the increase in skew angle contribute to the decrease in strength of beams. This is possible due to the torsional effect which rotates or twists the beams. So from this case, it can be conclude that when CFRP is going to be used to strengthen skew beams, the design engineers need to consider the skew angle of the beams as the beams with different skew angle might need different intensity of the strengthening to reach the same effect.

As a conclusion, the objectives of this study are achieved. From the results, it is proved that the perpendicularly wrapped CFRP strips can strengthen the skew beams in shear better than the diagonally wrapped CFRP strips with an exception that the diagonally wrapped CFRP allow more deflection to the beam before failure. While in terms of skew angle, apparently this skew angle affects the shear strengthening of the skew beams. The strengthening effects on the beams decreased as the skew angle increased so for structures with different skew angle, the strength and the strengthening effect might be different from the one point to another possibly due to the torsional effect. However deeper studies need to be done by the researchers to come out with the analytical and numerical reasoning for this condition.

In this project, all the strengthened beams failed in flexural mode except Beam 3 which failed due to the peeling of CFRP strips which might results from the poor curing technique. As both control beams failed in shear mode, so it is verified that the CFRP can strengthen the shear strength of the beams due to its stiffness thus fully mobilized the tensile reinforcement of the RC beam's steel bars and make it failed in bending. The failure in flexural mode is favorable compared to the shear mode because shear mode arises abruptly without any forewarning. Although the results obtained from this project are not as high as achieved by other researchers which is stated in the literature, the objective and the scope of study of this project has been covered and achieved successfully.

5.2 Recommendations

The main constraint for this project is time. Further study need to be done especially by the Post Graduate (PG) students as they have a longer research period. By having a longer time, more samples can be prepared and tested instead of just six, so if one of the samples for example in this project, Beam 3 exhibits the unexpected results, selective method can be done instead of just throw it out from comparison. By having more samples it can act as backup when there is any unforeseen conditions occurred. Other than that, it is good for the future research students to opt for dynamic load test to demonstrate the real cyclic loading conditions faced by the bridges due to the traffics loads. Dynamic load test might take a week for each beam, so it is not possible for the FYP students to manage that in time, PG students will have more research time to do on dynamic load.

For the PG students, they can opt for other CFRP configuration such as having more variation in CFRP inclination and more samples so that the relation between CFRP inclinations and the strengthening of the beams can be observed and communicated better. Other than that, the testing on more skew angles can be done so that the actual situations happens to the skew beams such as the torsional effect can be deeply analyze so that analytical and numerical approach can be established. In fact, other than focus only on shear strengthening of skew beams, it is good if the future research students can combine the shear and flexural strengthening together which might results into a better strengthening.

Having a good project is not adequate if it is not supported with a good funding. This project requires extra funding especially for the material procurements. Having extra funding or at least emergency budget can help the FYP students in preparing for any unforeseen circumstances in order to come out with a research with high quality. On funding, the future research students also can use CFRP fabric as the strengthening material instead of CFRP strip. Although CFRP fabric is more expensive compared to CFRP strip but CFRP fabric is believed to be more reliable as it can be directly wrapped around the beam. For CFRP strips, it is not possible to bend it into u-wrap so by having it into 3 pieces, some researchers blamed this as one of the reason which affect the strengthening compared to one sheet of CFRP fabric.

In terms of technology, more tools which are required should be prepared by the university because it is crucial in the learning process of civil engineering not only for this project. For example it is good if university can provide bar bending machine which is essential to bend the reinforcement bars and stirrups precisely. For the concrete mixing part, the available concrete mixer is too small and in fact some of the parts are already dilapidated which lead to the inhomogeneous of the mix. At the same time, this technology can upgrade the quality of the research and motivate the researchers in doing better. Specifically for this project, sand blasting equipment is vital to ensure a high-quality surface treatment so that it might not affect the bonding between concrete, epoxy and CFRP. Although using and blasting is better, but the current practice of using grinder and sand paper for surface treatment are still acceptable and in fact economical.

For the training part, the students need to be trained on how to handle certain machine for example 500 kN dynamic machine instead of just depend on the technicians. This training will speed up the process where the students can operate themselves the machine rather than need to wait for the technicians which also need to perform other responsibilities. While for the technicians, it is crucial for them to know the basic techniques on how to resolve small problems occurred to the machines or equipments so that there will be no lagging for the students in completing their tasks.

A documentation of the study and technology also must be clearly written and compiled so that other student or practitioner can have basic knowledge and information of the project background before proceeding with the project.

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APPENDICES

Appendix 1-1: Gantt Chart for Semester 1 (Jan 2009)

Planning of Work (Semester 1)
Noor Safwan bin Muhamad (7467)
"Shear Strengthening of Skew RC Beams Using CFRP"

No	Details	W1	W2	W3	W4	W5	W6	W7	W8	W9	MS	W10	W11	W12	W13	W14	SW
1	Selection of Topic																
2	Preliminary Research Work																
3	Lab Work																
	Trial Mix																
	Formwork																
	Reinforcement bars																
	Beam Casting	To be done during semester break															
	Applying CFRP	To be done next semester															
	Beam Testing	To be done next semester															
4	Submission of Progress Report 1						TBA										
5	Submission of Interim Report													TBA			
6	Oral presentation																TBA

TBA	Suggested Milestone
	Process
MS	Midsem Break
SW	Study Week

Appendix 1-2: Gantt Chart for Semester 2 (July 2009)

Planning of Work (Semester 2)

Noor Safwan bin Muhamad (7467)

"Shear Strengthening of Skew RC Beams Using CFRP"

No	Details	W1	W2	HN	W3	W4	W5	W6	W7	W8	MS	W9	W10	W11	W12	W13	W14
1	Research work continues																
2	Lab Work																
	Control Beam Testing																
	Applying CFRP																
	Beam Testing																
3	Seminar																
	IEM Talk				12/8												
	Talk on Statistics						26/8										
4	Submission of Progress Report II							3/9									
5	Poster Exhibition												TBA				
6	Submission of Dissertation																
	Soft Bound													TBA			
	Hard Bound															TBA	
7	Oral Presentation															TBA	

TBA	Suggested Milestone
	Process
HN	H1N1 Break
MS	Midsem Break

Appendix 2-1: Laboratory data for Beam 4

Note: Flow from top to bottom, left to right

Deflection (mm)	Load (kN)
0.3	0.87
0.298	0.9
0.301	0.97
0.299	1.02
0.299	1.06
0.298	1.11
0.301	1.16
0.31	1.22
0.298	1.27
0.275	1.32
0.284	1.37
0.297	1.41
0.309	1.46
0.32	1.51
0.327	1.55
0.329	1.6
0.329	1.65
0.332	1.7
0.333	1.75
0.338	1.8
0.333	1.85
0.327	1.9
0.324	1.94
0.318	1.98
0.318	2.03
0.318	2.08
0.315	2.13
0.316	2.2
0.318	2.25
0.214	2.3
0.203	2.36
0.242	2.37
0.276	2.44
0.296	2.49
0.312	2.55
0.321	2.59
0.332	2.64
0.339	2.69
0.34	2.75
0.341	2.79
0.34	2.84
0.338	2.88
0.339	2.92
0.343	2.98
0.349	3.03
0.351	3.08
0.355	3.13
0.363	3.18
0.341	3.23
0.357	3.28
0.366	3.33
0.374	3.39
0.381	3.45
0.389	3.5
0.395	3.55
0.407	3.6
0.411	3.65
0.439	3.7
0.441	3.75
0.499	3.79
0.539	3.84
0.564	3.88
0.586	3.93
0.598	3.98
0.611	4.02
0.62	4.07
0.626	4.11
0.633	4.16
0.639	4.21
0.642	4.25
0.645	4.3
0.648	4.34
0.652	4.4
0.655	4.44
0.659	4.49
0.661	4.54
0.663	4.58
0.667	4.63
0.671	4.68
0.673	4.72
0.675	4.76
0.677	4.81
0.682	4.86
0.685	4.91
0.686	4.95
0.688	5
0.691	5.05
0.697	5.11
0.699	5.15
0.701	5.21
0.704	5.26
0.708	5.31
0.711	5.37
0.713	5.42
0.714	5.47
0.717	5.52
0.72	5.56
0.722	5.62
0.723	5.66
0.726	5.71
0.731	5.75
0.734	5.8
0.735	5.86
0.734	5.9
0.724	5.95
0.708	6.02
0.696	6.07
0.682	6.13
0.681	6.18
0.678	6.22
0.672	6.27
0.676	6.31
0.661	6.36
0.648	6.41
0.645	6.45
0.643	6.49
0.645	6.53
0.646	6.59
0.652	6.64
0.655	6.69
0.66	6.74
0.661	6.79
0.665	6.84
0.664	6.88
0.665	6.93
0.665	6.99
0.664	7.04
0.657	7.09
0.654	7.14
0.648	7.19
0.651	7.24
0.649	7.29
0.642	7.34

0.642	7.38
0.646	7.42
0.652	7.47
0.647	7.51
0.634	7.56
0.636	7.6
0.629	7.66
0.634	7.71
0.637	7.78
0.634	7.83
0.627	7.88
0.618	7.94
0.609	7.99
0.595	8.05
0.582	8.09
0.579	8.14
0.523	8.18
0.633	8.23
0.713	8.28
0.762	8.32
0.798	8.37
0.824	8.41
0.843	8.45
0.857	8.5
0.867	8.54
0.875	8.59
0.881	8.63
0.886	8.69
0.887	8.76
0.891	8.81
0.895	8.87
0.9	8.92
0.904	8.97
0.904	9.02
0.908	9.07
0.91	9.11
0.913	9.15
0.916	9.2
0.917	9.25
0.919	9.3
0.923	9.35
0.926	9.39
0.93	9.44
0.933	9.49
0.936	9.54
0.939	9.59
0.941	9.64

0.946	9.69
0.948	9.74
0.95	9.79
0.951	9.84
0.953	9.88
0.958	9.94
0.963	9.98
0.966	10.04
0.967	10.09
0.969	10.13
0.974	10.18
0.977	10.23
0.98	10.27
0.983	10.33
0.985	10.38
0.991	10.46
0.996	10.51
1.001	10.57
1.005	10.62
1.009	10.67
1.013	10.72
1.019	10.76
1.025	10.79
1.03	10.82
1.034	10.87
1.039	10.93
1.044	10.99
1.049	11.05
1.054	11.11
1.057	11.16
1.061	11.23
1.065	11.28
1.07	11.33
1.074	11.38
1.076	11.43
1.078	11.48
1.081	11.53
1.085	11.57
1.089	11.62
1.09	11.66
1.091	11.71
1.095	11.76
1.098	11.8
1.101	11.85
1.101	11.89
1.105	11.94
1.109	11.98

1.112	12.03
1.113	12.08
1.116	12.12
1.12	12.17
1.121	12.22
1.122	12.26
1.111	12.31
1.119	12.36
1.123	12.41
1.126	12.46
1.131	12.5
1.135	12.54
1.139	12.59
1.14	12.64
1.144	12.7
1.148	12.75
1.151	12.81
1.153	12.86
1.156	12.91
1.159	12.97
1.162	13.01
1.165	13.06
1.166	13.11
1.167	13.16
1.17	13.21
1.175	13.26
1.179	13.3
1.181	13.35
1.183	13.41
1.186	13.47
1.189	13.52
1.192	13.56
1.195	13.61
1.197	13.66
1.199	13.71
1.2	13.75
1.202	13.79
1.207	13.85
1.21	13.89
1.212	13.94
1.213	14
1.216	14.05
1.22	14.11
1.222	14.16
1.223	14.21
1.225	14.25
1.229	14.3

1.232	14.34
1.234	14.39
1.234	14.44
1.236	14.48
1.239	14.53
1.244	14.58
1.246	14.62
1.247	14.67
1.25	14.72
1.252	14.77
1.254	14.81
1.256	14.87
1.258	14.94
1.262	15
1.266	15.06
1.271	15.1
1.275	15.15
1.277	15.2
1.279	15.25
1.283	15.3
1.286	15.34
1.289	15.39
1.292	15.44
1.293	15.48
1.296	15.51
1.302	15.52
1.313	15.72
1.322	15.83
1.391	15.79
1.405	15.86
1.408	15.9
1.416	15.95
1.426	16.02
1.432	16.07
1.439	16.12
1.443	16.17
1.447	16.21
1.451	16.26
1.456	16.31
1.459	16.36
1.464	16.41
1.468	16.45
1.471	16.5
1.474	16.53
1.478	16.58
1.483	16.63
1.488	16.68
1.494	16.73
1.497	16.78
1.499	16.83
1.503	16.87
1.509	16.92
1.518	16.77
1.566	17.08
1.576	17.07
1.586	17.12
1.596	17.15
1.609	17.23
1.618	17.3
1.625	17.36
1.631	17.42
1.637	17.46
1.646	17.51
1.652	17.55
1.658	17.59
1.664	17.64
1.669	17.68
1.674	17.73
1.682	17.63
1.81	17.78
1.829	17.88
1.836	17.9
1.843	17.96
1.849	18.01
1.854	18.07
1.86	18.12
1.866	18.17
1.872	18.22
1.877	18.27
1.881	18.31
1.886	18.36
1.892	18.41
1.896	18.46
1.901	18.51
1.904	18.56
1.908	18.61
1.915	18.66
1.92	18.7
1.926	18.75
1.931	18.8
1.935	18.84
1.941	18.9
1.946	18.94
1.953	18.99
1.959	19.03
1.964	19.07
1.967	19.12
1.973	19.16
1.978	19.22
1.984	19.26
1.991	19.31
1.999	19.36
2.002	19.4
2.005	19.45
2.011	19.49
2.019	19.55
2.026	19.6
2.032	19.65
2.037	19.7
2.043	19.75
2.049	19.8
2.058	19.85
2.062	19.89
2.066	19.94
2.07	20
2.077	20.04
2.084	20.09
2.091	20.14
2.097	20.19
2.102	20.24
2.108	20.29
2.114	20.34
2.123	20.4
2.13	20.45
2.134	20.51
2.14	20.55
2.143	20.6
2.149	20.65
2.155	20.69
2.161	20.74
2.167	20.78
2.172	20.83
2.177	20.88
2.185	20.93
2.191	20.97
2.196	21.02
2.2	21.07
2.205	21.12
2.21	21.17
2.216	21.22
2.222	21.26

2.225	21.31
2.206	21.36
2.214	21.4
2.228	21.45
2.239	21.49
2.249	21.54
2.259	21.59
2.268	21.5
2.365	21.78
2.386	21.83
2.306	21.89
2.348	21.92
2.375	21.95
2.395	22
2.411	22.05
2.423	22.12
2.434	22.18
2.445	22.23
2.455	22.28
2.461	22.32
2.467	22.37
2.472	22.42
2.478	22.47
2.485	22.51
2.492	22.56
2.497	22.61
2.502	22.66
2.508	22.71
2.516	22.76
2.523	22.8
2.53	22.86
2.536	22.9
2.541	22.95
2.548	23
2.554	23.04
2.56	23.09
2.563	23.14
2.569	23.19
2.574	23.23
2.581	23.28
2.588	23.33
2.594	23.38
2.601	23.43
2.606	23.47
2.613	23.51
2.621	23.56
2.625	23.61

2.63	23.65
2.632	23.69
2.638	23.74
2.647	23.79
2.653	23.84
2.658	23.89
2.665	23.94
2.671	23.98
2.681	24.04
2.685	24.09
2.69	24.13
2.697	24.18
2.702	24.22
2.708	24.27
2.711	24.32
2.717	24.36
2.723	24.41
2.731	24.46
2.738	24.51
2.743	24.56
2.75	24.62
2.756	24.67
2.761	24.72
2.765	24.77
2.769	24.82
2.776	24.86
2.784	24.92
2.79	24.97
2.797	25.01
2.804	25.06
2.812	25.11
2.818	25.16
2.825	25.21
2.83	25.26
2.836	25.32
2.843	25.36
2.85	25.41
2.855	25.46
2.86	25.51
2.864	25.56
2.869	25.6
2.874	25.65
2.882	25.7
2.889	25.75
2.895	25.79
2.9	25.84
2.905	25.89

2.91	25.93
2.918	25.98
2.962	25.3
3.06	26.16
3.073	26.24
3.082	26.26
3.091	26.33
3.099	26.39
3.11	26.44
3.117	26.49
3.122	26.54
3.128	26.59
3.135	26.64
3.143	26.69
3.151	26.73
3.158	26.78
3.165	26.83
3.17	26.87
3.176	26.93
3.181	26.97
3.186	27.02
3.192	27.07
3.198	27.12
3.205	27.17
3.211	27.21
3.219	27.25
3.225	27.3
3.23	27.35
3.235	27.4
3.241	27.44
3.246	27.49
3.252	27.53
3.258	27.54
3.338	27.7
3.355	27.71
3.366	27.8
3.367	27.83
3.35	27.85
3.363	27.9
3.378	27.96
3.384	28.02
3.392	28.06
3.405	28.11
3.397	28.16
3.41	28.2
3.421	28.25
3.43	28.3

3.437	28.33
3.537	28.37
3.573	28.47
3.586	28.49
3.597	28.55
3.61	28.61
3.618	28.66
3.626	28.71
3.633	28.76
3.64	28.8
3.646	28.85
3.652	28.9
3.659	28.95
3.665	28.99
3.672	29.04
3.681	29.09
3.688	29.14
3.695	29.19
3.701	29.24
3.708	29.28
3.715	29.34
3.72	29.39
3.725	29.43
3.73	29.48
3.735	29.52
3.741	29.57
3.747	29.62
3.753	29.66
3.759	29.7
3.766	29.75
3.774	29.8
3.779	29.84
3.784	29.89
3.788	29.94
3.794	29.99
3.801	30.04
3.807	30.09
3.815	30.13
3.822	30.18
3.83	30.23
3.837	30.28
3.844	30.33
3.849	30.37
3.855	30.42
3.862	30.47
3.871	30.52
3.878	30.56

3.883	30.61
3.888	30.65
3.893	30.71
3.899	30.75
3.907	30.81
3.914	30.85
3.922	30.91
3.929	30.97
3.936	31.02
3.943	31.07
3.952	31.13
3.961	31.17
3.967	31.22
3.972	31.28
3.976	31.32
3.917	31.37
3.754	31.42
3.711	31.47
3.78	31.52
3.851	31.57
3.91	31.62
3.951	31.67
3.979	31.72
4.001	31.76
4.023	31.81
4.036	31.86
4.047	31.9
4.054	31.95
4.046	31.99
4.063	32.05
4.075	32.1
4.086	32.14
4.095	32.19
4.104	32.24
4.11	32.29
4.118	32.33
4.125	32.38
4.132	32.43
4.141	32.47
4.147	32.53
4.153	32.58
4.16	32.63
4.166	32.68
4.177	32.73
4.184	32.78
4.191	32.83
4.196	32.87

4.202	32.92
4.211	32.99
4.218	33.04
4.223	33.09
4.23	33.13
4.236	33.18
4.243	33.23
4.249	33.28
4.257	33.33
4.265	33.38
4.272	33.42
4.278	33.48
4.286	33.53
4.293	33.57
4.299	33.62
4.305	33.66
4.309	33.71
4.316	33.76
4.322	33.81
4.328	33.85
4.335	33.9
4.344	33.96
4.351	34
4.358	34.05
4.365	34.1
4.373	34.15
4.381	34.21
4.387	34.25
4.393	34.31
4.397	34.35
4.405	34.4
4.414	34.45
4.42	34.5
4.427	34.55
4.433	34.59
4.439	34.64
4.445	34.7
4.453	34.74
4.46	34.79
4.467	34.83
4.474	34.88
4.48	34.93
4.487	34.98
4.493	35.03
4.498	35.08
4.502	35.13
4.512	35.18

4.518	35.23	4.823	37.58	5.142	39.87
4.526	35.28	4.834	37.63	5.149	39.92
4.535	35.33	4.845	37.68	5.155	39.97
4.543	35.38	4.848	37.73	5.16	40.02
4.548	35.44	4.859	37.78	5.169	40.09
4.553	35.48	4.867	37.83	5.176	40.15
4.561	35.53	4.873	37.87	5.183	40.21
4.568	35.58	4.879	37.92	5.191	40.26
4.576	35.63	4.886	37.96	5.199	40.25
4.583	35.68	4.893	38.01	5.241	40.45
4.587	35.74	4.901	38.06	5.249	40.38
4.594	35.78	4.908	38.1	5.261	40.5
4.602	35.83	4.915	38.15	5.273	40.6
4.61	35.88	4.922	38.2	5.285	40.68
4.617	35.92	4.928	38.25	5.292	40.73
4.621	35.97	4.935	38.3	5.299	40.76
4.625	36.02	4.941	38.34	5.303	40.79
4.632	36.07	4.948	38.4	5.308	40.82
4.639	36.12	4.958	38.46	5.312	40.86
4.648	36.18	4.964	38.51	5.32	40.9
4.654	36.22	4.97	38.56	5.326	40.95
4.662	36.27	4.974	38.61	5.332	41
4.668	36.33	4.98	38.66	5.338	41.05
4.675	36.39	4.988	38.72	5.344	41.1
4.682	36.45	4.995	38.77	5.351	41.15
4.693	36.51	5.002	38.82	5.358	41.19
4.698	36.55	5.006	38.87	5.364	41.24
4.705	36.6	5.014	38.92	5.371	41.29
4.711	36.65	5.021	38.98	5.378	41.34
4.718	36.69	5.026	39.02	5.384	41.39
4.724	36.75	5.032	39.07	5.389	41.43
4.73	36.79	5.037	39.11	5.394	41.47
4.739	36.84	5.042	39.16	5.401	41.53
4.746	36.89	5.051	39.21	5.408	41.57
4.751	36.94	5.058	39.25	5.414	41.62
4.758	36.98	5.064	39.3	5.416	41.66
4.765	37.03	5.07	39.34	5.424	41.71
4.773	37.08	5.075	39.39	5.429	41.76
4.779	37.14	5.082	39.44	5.436	41.81
4.786	37.18	5.088	39.48	5.443	41.86
4.792	37.24	5.094	39.53	5.449	41.91
4.792	37.29	5.1	39.57	5.455	41.95
4.798	37.34	5.106	39.62	5.46	42.01
4.763	37.39	5.116	39.68	5.466	42.06
4.768	37.44	5.121	39.72	5.472	42.11
4.79	37.48	5.128	39.77	5.479	42.16
4.808	37.53	5.135	39.82	5.489	42.2

5.495	42.26
5.501	42.3
5.507	42.34
5.513	42.39
5.521	42.43
5.528	42.49
5.534	42.53
5.539	42.58
5.544	42.63
5.553	42.68
5.559	42.73
5.564	42.77
5.571	42.82
5.577	42.88
5.586	42.94
5.592	42.99
5.597	43.04
5.602	43.09
5.606	43.13
5.61	43.19
5.615	43.23
5.62	43.27
5.626	43.32
5.633	43.36
5.638	43.41
5.644	43.46
5.65	43.48
5.658	43.51
5.671	43.54
5.697	43.77
5.715	43.87
5.726	43.91
5.732	43.93
5.739	43.95
5.748	43.99
5.753	44.03
5.759	44.08
5.764	44.12
5.769	44.17
5.778	44.23
5.785	44.27
5.792	44.32
5.798	44.37
5.804	44.42
5.812	44.47
5.819	44.51
5.826	44.57

5.831	44.61
5.835	44.66
5.84	44.71
5.846	44.75
5.853	44.8
5.857	44.84
5.862	44.89
5.867	44.94
5.874	44.98
5.881	45.03
5.888	45.08
5.894	45.12
5.898	45.17
5.904	45.22
5.909	45.26
5.916	45.3
5.921	45.35
5.926	45.32
5.938	45.3
5.971	45.53
5.992	45.68
5.997	45.66
6.002	45.68
6.007	45.72
6.013	45.76
6.02	45.81
6.026	45.86
6.031	45.91
6.035	45.96
6.038	46.01
6.046	46.05
6.052	46.1
6.057	46.15
6.063	46.19
6.052	46.24
6.049	46.29
6.063	46.34
6.074	46.39
6.081	46.43
6.088	46.48
6.098	46.52
6.105	46.57
6.112	46.62
6.118	46.66
6.124	46.71
6.132	46.75
6.138	46.8

6.145	46.85
6.151	46.89
6.16	46.95
6.167	47
6.174	47.06
6.178	47.11
6.184	47.15
6.189	47.2
6.195	47.25
6.202	47.3
6.207	47.34
6.212	47.39
6.216	47.43
6.221	47.48
6.229	47.53
6.234	47.57
6.24	47.62
6.224	47.66
6.219	47.71
6.237	47.76
6.25	47.8
6.259	47.85
6.267	47.9
6.275	47.95
6.28	48
6.288	48.05
6.296	48.1
6.303	48.15
6.308	48.2
6.312	48.25
6.318	48.3
6.323	48.34
6.329	48.38
6.332	48.43
6.338	48.49
6.344	48.53
6.35	48.58
6.356	48.63
6.364	48.68
6.369	48.73
6.373	48.78
6.379	48.83
6.385	48.88
6.394	48.94
6.4	48.99
6.405	49.04
6.41	49.09

6.416	49.14
6.424	49.19
6.43	49.24
6.436	49.29
6.441	49.33
6.445	49.38
6.451	49.43
6.456	49.48
6.463	49.52
6.47	49.57
6.476	49.61
6.481	49.66
6.487	49.71
6.494	49.75
6.499	49.8
6.504	49.85
6.509	49.91
6.514	49.96
6.518	50.01
6.523	50.06
6.529	50.11
6.538	50.17
6.545	50.21
6.551	50.26
6.559	50.31
6.565	50.36
6.572	50.42
6.578	50.47
6.584	50.52
6.589	50.57
6.595	50.62
6.598	50.67
6.604	50.72
6.609	50.77
6.615	50.81
6.621	50.86
6.628	50.92
6.633	50.96
6.638	51.01
6.644	51.06
6.648	51.11
6.656	51.16
6.662	51.2
6.667	51.25
6.672	51.29
6.678	51.34
6.687	51.39

6.693	51.44
6.698	51.48
6.703	51.53
6.708	51.58
6.713	51.63
6.719	51.67
6.725	51.72
6.73	51.77
6.736	51.82
6.741	51.87
6.746	51.92
6.751	51.96
6.757	52.01
6.765	52.06
6.77	52.11
6.776	52.16
6.782	52.22
6.788	52.27
6.793	52.33
6.799	52.38
6.805	52.43
6.812	52.48
6.818	52.53
6.827	52.59
6.832	52.64
6.837	52.68
6.842	52.73
6.847	52.77
6.852	52.83
6.857	52.88
6.862	52.93
6.867	52.99
6.872	53.04
6.879	53.09
6.884	53.14
6.891	53.18
6.898	53.23
6.904	53.27
6.913	53.32
6.919	53.37
6.924	53.41
6.929	53.46
6.934	53.5
6.939	53.55
6.944	53.6
6.949	53.64
6.954	53.69

6.961	53.73
6.968	53.78
6.972	53.83
6.977	53.87
6.983	53.92
6.988	53.96
6.992	54.02
6.995	54.06
6.999	54.1
7.007	54.16
7.015	54.23
7.021	54.29
7.028	54.35
7.036	54.4
7.044	54.45
7.05	54.5
7.055	54.55
7.059	54.6
7.067	54.66
7.073	54.71
7.079	54.76
7.084	54.82
7.09	54.87
7.095	54.92
7.102	54.97
7.107	55.02
7.112	55.07
7.117	55.12
7.123	55.17
7.131	55.22
7.137	55.27
7.142	55.31
7.147	55.35
7.151	55.41
7.157	55.45
7.163	55.5
7.171	55.54
7.177	55.59
7.181	55.64
7.187	55.69
7.193	55.73
7.199	55.78
7.205	55.83
7.209	55.87
7.215	55.93
7.22	55.97
7.227	56.02

7.232	56.07
7.237	56.13
7.242	56.18
7.247	56.23
7.253	56.28
7.258	56.33
7.265	56.39
7.27	56.44
7.276	56.48
7.282	56.53
7.288	56.58
7.296	56.63
7.301	56.68
7.307	56.73
7.311	56.79
7.317	56.84
7.326	56.9
7.333	56.95
7.339	57
7.345	57.05
7.349	57.1
7.356	57.14
7.363	57.19
7.369	57.24
7.374	57.28
7.378	57.33
7.384	57.39
7.39	57.44
7.397	57.5
7.403	57.54
7.407	57.59
7.414	57.64
7.42	57.69
7.426	57.73
7.432	57.78
7.436	57.83
7.442	57.88
7.448	57.93
7.454	57.97
7.461	58.03
7.466	58.08
7.472	58.13
7.477	58.18
7.483	58.22
7.489	58.27
7.494	58.33
7.496	58.37

7.501	58.42
7.506	58.46
7.509	58.51
7.518	58.56
7.524	58.61
7.529	58.66
7.535	58.71
7.541	58.76
7.551	58.82
7.558	58.86
7.563	58.91
7.569	58.96
7.573	59
7.58	59.05
7.586	59.09
7.592	59.14
7.596	59.19
7.601	59.23
7.605	59.28
7.611	59.33
7.618	59.37
7.623	59.41
7.627	59.46
7.631	59.52
7.635	59.56
7.641	59.61
7.648	59.66
7.654	59.71
7.661	59.76
7.667	59.81
7.673	59.86
7.677	59.91
7.683	59.96
7.69	60.02
7.695	60.07
7.702	60.13
7.707	60.18
7.713	60.22
7.718	60.27
7.726	60.32
7.732	60.37
7.739	60.42
7.743	60.47
7.748	60.52
7.752	60.57
7.758	60.62
7.765	60.67

7.77	60.72
7.774	60.77
7.78	60.82
7.786	60.87
7.795	60.92
7.801	60.96
7.805	61.01
7.81	61.07
7.815	61.11
7.821	61.17
7.825	61.21
7.831	61.26
7.836	61.32
7.84	61.36
7.838	61.41
7.845	61.46
7.853	61.51
7.854	61.56
7.83	61.61
7.82	61.66
7.812	61.71
7.822	61.75
7.839	61.81
7.851	61.86
7.862	61.91
7.875	61.95
7.895	62.01
7.897	62.05
7.898	62.1
7.914	62.15
7.899	62.19
7.844	62.25
7.862	62.3
7.898	62.34
7.924	62.39
7.941	62.44
7.957	62.49
7.969	62.54
7.979	62.59
7.988	62.63
7.997	62.68
8.003	62.73
8.01	62.77
8.017	62.83
8.025	62.89
8.032	62.95
8.041	63.01

8.894	69.98	9.18	72.33	9.477	74.61
8.899	70.03	9.186	72.37	9.48	74.66
8.905	70.08	9.191	72.42	9.487	74.7
8.911	70.13	9.196	72.48	9.493	74.75
8.917	70.18	9.202	72.52	9.499	74.79
8.924	70.23	9.208	72.57	9.508	74.83
8.931	70.29	9.215	72.61	9.515	74.87
8.939	70.34	9.221	72.66	9.522	74.91
8.945	70.4	9.228	72.71	9.53	74.97
8.95	70.45	9.234	72.76	9.54	75.06
8.957	70.5	9.239	72.81	9.55	75.13
8.962	70.55	9.244	72.86	9.558	75.2
8.967	70.6	9.249	72.9	9.565	75.26
8.972	70.65	9.255	72.95	9.573	75.31
8.978	70.7	9.26	73	9.58	75.37
8.984	70.75	9.266	73.05	9.588	75.43
8.992	70.8	9.272	73.09	9.596	75.48
8.999	70.85	9.279	73.14	9.603	75.53
9.004	70.89	9.285	73.19	9.61	75.57
9.011	70.94	9.292	73.24	9.617	75.61
9.017	70.99	9.299	73.3	9.623	75.67
9.022	71.04	9.306	73.34	9.63	75.71
9.028	71.09	9.307	73.39	9.636	75.76
9.034	71.13	9.316	73.42	9.642	75.8
9.04	71.18	9.323	73.46	9.649	75.84
9.045	71.23	9.33	73.48	9.657	75.88
9.051	71.28	9.338	73.54	9.665	75.89
9.056	71.32	9.344	73.6	9.673	75.92
9.061	71.37	9.352	73.67	9.68	75.98
9.066	71.41	9.358	73.72	9.686	76.03
9.071	71.46	9.364	73.78	9.693	76.08
9.077	71.51	9.371	73.83	9.701	76.12
9.084	71.56	9.378	73.88	9.708	76.18
9.091	71.61	9.387	73.94	9.716	76.22
9.097	71.66	9.394	73.99	9.725	76.28
9.102	71.71	9.401	74.03	9.734	76.34
9.108	71.76	9.408	74.08	9.742	76.39
9.114	71.8	9.414	74.13	9.75	76.43
9.121	71.85	9.42	74.18	9.758	76.48
9.127	71.9	9.425	74.23	9.765	76.53
9.135	71.96	9.432	74.28	9.773	76.58
9.14	72.02	9.436	74.32	9.78	76.63
9.146	72.07	9.443	74.37	9.787	76.66
9.152	72.12	9.451	74.42	9.793	76.71
9.159	72.17	9.457	74.47	9.801	76.76
9.166	72.23	9.464	74.51	9.808	76.82
9.173	72.28	9.47	74.56	9.816	76.86

9.824	76.91
9.831	76.92
9.84	76.97
9.851	77.02
9.86	77.04
9.871	77.1
9.882	77.15
9.894	77.21
9.905	77.3
9.917	77.38
9.93	77.37
9.944	77.44
9.96	77.5
9.976	77.54
9.991	77.58
10.007	77.64
10.022	77.69
10.039	77.72
10.058	77.73
10.081	77.76
10.127	77.78
10.341	77.78
10.553	78.02
10.735	77.93
10.901	78.17
11.023	78.21
11.129	78.28
11.223	78.36
11.294	78.41
11.356	78.44
11.417	78.53
11.47	78.6
11.523	78.64
11.567	78.7
11.61	78.76
11.651	78.81
11.69	78.87
11.731	78.91
11.765	78.94
11.798	78.99
11.831	79.05
11.865	79.11
11.901	79.18
11.934	79.23
11.968	79.27
12	79.32
12.036	79.38

12.066	79.43
12.096	79.47
12.131	79.53
12.164	79.57
12.196	79.63
12.227	79.67
12.26	79.73
12.292	79.78
12.322	79.81
12.358	79.87
12.394	79.93
12.425	79.98
12.454	80.01
12.483	80.05
12.519	80.08
12.55	80.12
12.582	80.15
12.613	80.19
12.647	80.22
12.681	80.26
12.715	80.3
12.754	80.32
12.788	80.35
12.823	80.37
12.86	80.38
12.895	80.42
12.934	80.45
12.976	80.51
13.022	80.55
13.081	80.7
13.138	80.75
13.203	80.79
13.259	80.82
13.317	80.81
13.375	80.82
13.44	80.9
13.526	81
13.601	81.01
13.675	81.09
13.753	81.14
13.829	81.19
13.916	81.23
13.995	81.27
14.079	81.22
14.299	80.81
14.771	80.95
15.223	80.99

15.677	81.21
16.05	81.29
16.555	80.86
17.143	81.02
17.77	81.16
18.291	81.32
18.738	81.48
19.126	81.59
19.484	81.7
19.856	81.76
20.174	81.86
20.511	81.95
20.787	82.02
21.081	82.1
21.327	82.17
21.565	82.24
21.816	82.31
22.035	82.36
22.247	82.43
22.478	82.49
22.672	82.54
22.857	82.58
23.067	82.64
23.254	82.66
23.44	82.69
23.626	82.7
23.811	82.74
24.018	82.8
24.185	82.81
24.352	82.8
24.554	82.83
24.79	**82.88**
25.003	82.85
25.26	82.51
26.896	80.45
28.698	81.52
29.762	82.16
30.613	82.39
31.509	82.59
32.306	82.56
33.186	82.32
34.166	82.17
35.224	82.16
36.323	82.15
37.663	81.77
40.608	81.23
42.52	81.98

43.935	80.53
43.891	78.8
43.825	77.65
43.769	76.83
43.727	76.23
43.707	75.92
43.715	76